Institute for Aerospace Engineering

Luftfahrzeugbau und Leichtbau

Identification and Assessment of Innovative Technologies for unmanned Urban Air Mobility Vehicles

Bachelorarbeit

von

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27. Oktober 2023

Eidesstattliche Erklärung

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Abstract

This thesis presents a novel conceptual design methodology, the Advanced Morphological Approach, developed by the Chair of Aircraft Design and Aerostructures at Technische Universität Berlin. The primary objective of this approach is to enhance designers' creativity and address the formidable challenges of uncertainty that characterize the initial phases of aircraft design. This work explores the application of this methodology within the context of designing unmanned Urban Air Mobility Vehicles (UAM), setting the stage for further investigation.

The thesis commences with a comprehensive literature review, establishing the state-of-the-art and theoretical foundations of the Advanced Morphological Approach and its underlying principles. It delves into the essence of the UAM concept, covering its diverse missions, requisite aircraft technologies, and technical specifications. It classifies UAM missions into categories such as passenger transport, cargo delivery, and emergency services.

Furthermore, the study extends to the domain of Unmanned Aerial Vehicles (UAVs), chosen as the appropriate aircraft for UAM. It provides an in-depth analysis of various UAV classes, applications, and aircraft types, categorizing them into fixed-wing, hybrid, multirotor, and helicopter classes. The components and primary functionalities of UAM systems are detailed.

The theoretical framework related to the Conceptual Design Phase and the Advanced Morphological Approach is discussed. The approach employs Morphological Analysis as a tool to address the complexities of structural synthesis in designing intricate systems.

The classification of aircraft according to mission requirements is then examined. The thesis presents tables categorizing suitable air vehicles for various UAM missions. It generates a list of reference UAVs, including their performance specifications, and employs this methodology for future UAM air taxi concepts, highlighting attributes, technological options, and system integration possibilities.

The study proceeds to create Morphological Matrices for fixed-wing aircraft, hybrid aircraft, and rotorcraft, using attributes identified through extensive literature review. These matrices provide a framework for generating a vast solution space of configurations for each design problem, thereby increasing the potential for identifying optimal solutions.

While a methodology for quantitative evaluation based on the Max-Min Normalization Method is proposed, limitations arise due to data availability and time constraints. A quantitative assessment of technological options and a qualitative comparison between technologies could not be completed.

This thesis acknowledges several limitations, including the challenges posed by the novelty of UAM and the complexity of hybrid aircraft attributes. The absence of comprehensive quantitative data for technology assessments in the UAM context also represents a notable limitation.

Future work is essential to address these limitations and continue the application of the Advanced Morphological Approach. Prioritizing the quantitative evaluation of criteria is crucial, as it will unlock subsequent phases of the approach. Additionally, exploring unconventional UAVs and their suitability for UAM applications and expanding the technology assessment to include a broader range of options represent promising directions for future research efforts.

Kurzfassung

Diese Arbeit präsentiert eine neuartige konzeptionelle Designmethodik, den Advanced Morphological Approach, entwickelt vom Lehrstuhl für Flugzeugentwurf und Leichtbau an der Technischen Universität Berlin. Das Hauptziel dieses Ansatzes besteht darin, die Kreativität der Designer zu fördern und die erheblichen Herausforderungen der Unsicherheit in den anfänglichen Phasen des Flugzeugdesigns zu bewältigen. Diese Arbeit untersucht die Anwendung dieser Methodik im Kontext des Designs unbemannter Urban Air Mobility-Fahrzeuge (UAM) und bereitet den Boden für weitere Untersuchungen vor.

Die Arbeit beginnt mit einer umfassenden Literaturrecherche, die den aktuellen Stand der Technik und die theoretischen Grundlagen des Advanced Morphological Approach und seiner zugrunde liegenden Prinzipien etabliert. Sie geht auf die Essenz des UAM-Konzepts ein, das seine vielfältigen Missionen, erforderlichen Flugzeugtechnologien und technischen Spezifikationen abdeckt. UAM-Missionen werden in Kategorien wie Passagiertransport, Frachtzustellung und Notdienste eingeteilt.

Darüber hinaus erstreckt sich die Studie auf das Gebiet der unbemannten Luftfahrzeuge (UAVs), die als geeignete Flugzeuge für UAM ausgewählt wurden. Sie bietet eine eingehende Analyse verschiedener UAV-Klassen, Anwendungen und Flugzeugtypen und kategorisiert sie in Klassen wie Starrflügler, Hybridflugzeuge, Multikopter und Hubschrauber. Die Komponenten und Hauptfunktionalitäten von UAM-Systemen werden ausführlich erläutert.

Der theoretische Rahmen im Zusammenhang mit der konzeptionellen Designphase und dem Advanced Morphological Approach wird diskutiert. Der Ansatz verwendet die

morphologische Analyse als Werkzeug, um die Komplexität der Struktursynthese beim Entwerfen komplexer Systeme zu bewältigen.

Die Klassifizierung von Flugzeugen nach Missionsanforderungen wird dann untersucht. Die Arbeit präsentiert Tabellen, die geeignete Luftfahrzeuge für verschiedene UAM-Missionen kategorisieren. Sie generiert eine Liste von Referenz-UAVs, einschließlich ihrer Leistungsspezifikationen, und verwendet diese Methodik für zukünftige Konzepte von UAM-Lufttaxis, die Attribute, technologische Optionen und Möglichkeiten zur Integration von Systemen hervorheben.

Die Studie geht zur Erstellung von morphologischen Matrizen für Starrflügel-, Hybrid- und Hubschrauberflugzeuge über, wobei Attribute identifiziert werden, die durch eine umfangreiche Literaturrecherche ermittelt wurden. Diese Matrizen bieten einen Rahmen für die Generierung eines breiten Lösungsraums von Konfigurationen für jedes Designproblem und erhöhen somit das Potenzial zur Identifizierung optimaler Lösungen.

Obwohl eine Methodik zur quantitativen Bewertung auf Basis der Max-Min. Normalisierungsmethode vorgeschlagen wird, ergeben sich aufgrund der Datenverfügbarkeit und zeitlicher Beschränkungen Einschränkungen. Eine quantitative Bewertung der technologischen Optionen und ein qualitativer Vergleich zwischen den Technologien konnten nicht abgeschlossen werden.

Diese Arbeit erkennt mehrere Einschränkungen an, darunter die Herausforderungen aufgrund der Neuheit von UAM und der Komplexität der Attribute von Hybridflugzeugen. Das Fehlen umfassender quantitativer Daten für Technologiebewertungen im UAM-Kontext stellt ebenfalls eine bemerkenswerte Einschränkung dar.

Zukünftige Arbeiten sind erforderlich, um diese Einschränkungen anzugehen und die Anwendung des Advanced Morphological Approach fortzusetzen. Die Priorisierung der quantitativen Bewertung von Kriterien ist entscheidend, da sie die folgenden Phasen des Ansatzes freischalten wird. Darüber hinaus versprechen vielversprechende Richtungen für zukünftige Forschungsbemühungen, die Eignung von unkonventionellen UAVs für UAM-Anwendungen zu untersuchen und die Technologiebewertung auf eine breitere Palette von Optionen auszudehnen.

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FAKULTÄT V

VERKEHRS- UND MASCHINENSYSTEME

Institut für
Luft- und Raumfahrt

Fachgebiet
Luftfahrzeugbau und Leichtbau

Prof. Dr.-Ing. A. Bardenhagen

Berlin, den 15. Juni 2023

Bachelor Thesis

for

Mr. Juan De Freitas, Matr.-Nr. 398862

Identification and Assessment of Innovative Technologies for unmanned Urban Air Mobility Vehicles

Topic background

The necessity for the rapid development and implementation of disruptive technologies in Aviation, as well as in regional and urban air mobility has never been higher. The Chair of Aircraft Design and Aerostructures intensively studies novel concept design methods for the upcoming generations of aircraft. These should incorporate optimal combinations of technology solutions such as electric propulsion, vertical takeoff and landing, etc. The multidisciplinary and qualitative character of the considered Advanced Morphological Approach (AMA) presents the method suitable also for the design of vehicles for Urban Air Mobility (UAM) purposes. In this context, the necessity arises to prepare a UAM use case for its study with the AMA. This requires not only the identification of relevant technologies for the design of such aircraft, but also to consider their integration and implementation.

Aims of the work

The first aim is to identify and categorize technological solutions for the conceptual aircraft design for UAM. For this purpose, relevant applications and missions of general purpose unmanned aerial vehicles (UAV) shall be identified as well as those for UAM purposes in particular. Based on this overview, the most prominent UAV types are to be categorized according to their missions. This shall allow the subsequent selection of major system functions of potential UAM vehicles and their definition as system attributes of one or more morphological matrices. Appropriate technology alternatives to fulfil the attributes shall be selected, by laying focus mostly on innovative solutions. The second aim consists of the development and conduction of quantitative (when possible) and or/qualitative evaluation of selected technologies, based on existing studies and literature. In order to prepare the data for an AMA use case, it is then required to transform all assessments (quantitative and qualitative) to a universal qualitative evaluation scale.

The main tasks to be completed are defined as follows:

1. Literature research on the following topics:
    a. The Morphological Analysis and the Advanced Morphological Approach as context of the work;
    b. Global UAV application domains and missions, focus on UAM;
    c. Identification and systematization of promising and existing configurations of UAVs and air taxis as well as their components relevant for conceptual design (focus on unconventional configurations and promising innovative technologies);
    d. Identification or/and derivation of integration possibilities for the technological solutions into the different UAV configurations.

2. Structuring and systematization of the defined UAV components into one or more morphological matrices:
    a. Categorization of the typical UAV types according to the identified mission/application purposes;
    b. Identification of appropriate UAV system attributes and technological options;
    c. Derivation of one or multiple morphological matrices based on the former categorization.

3. Technology assessment:
    a. Quantitative (when possible) and/or qualitative comparison of selected UAV technologies according to the criteria energy efficiency, emissions and required infrastructural adaptation;
    b. Selection or derivation of appropriate qualitative and/or quantitative evaluation scales;
    c. Transformation of the conducted evaluations into a common qualitative scale.

The work will be conducted at the Chair of Aircraft Design and Aerostructures under the supervision of M.Sc. Vladislav Todorov and the undersigned.

Prof. Dr.-Ing. Andreas Bardenhagen

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1 Introduction

1.1 Context

It is the aim of this work to present and prepare a use case scenario regarding the design of air vehicles suitable for Urban Air Mobility (UAM) for the further study of the Advanced Morphological Approach (AMA) as a conceptual design tool. The context of this thesis can be divided into two main topics that relate to each other: 1) the demand for novel aircraft; and 2) the conceptual design of these using the approach proposed by Bardenhagen and Rakov (2019).

The need for novel aircraft

In the present study, the necessity for novel aircraft concepts arises from two primary factors. Firstly, the aviation industry seeks a solution to effectively address climate change objectives. Secondly, the introduction of a new air transportation model inside cities, which also must have a climate-neutral footprint. The main reason to start the introduction of this work presenting these two subtopics is because every design project must be clearly justified.

Due to the progress of climate change and the growth of global aviation, rapid and innovative technologies are highly needed in the aviation industry. The demand for air transport is estimated to increase by an average of 4,3% per year over the next 20 years (ICAO 2023). However, the impact of aviation on the environment is significant. In 2017, commercial aviation was the second biggest source of greenhouse emissions of the transport sector in the EU, with a 13,9% share and a total of 3,8%

of CO2 emissions (European Commission 2021). Globally, 2,5% of CO2 emissions and 3,5% of anthropogenic climate change are contributed to commercial aviation, when also including non-CO2 radiation (NOx, soot particles, oxidized sulfur species, and others) (André 2022). This has led institutions such as the European Commission and the International Civil Aviation Organization Transport Association (ICAO) to set really ambitious goals to meet the Paris Agreement (European Commission 2021). Consequently, the aviation industry must progressively decrease its emissions while maintaining its development. The industry must address its obligations for greater efficiency and significant emission reductions, yet no immediate technological solution is in sight (Todorov et al. 2022*b*).

Not only innovative solutions are required for the current aviation market, but the industry is extending its development beyond the mobility between cities, countries, and continents to also be an option of mobility within cities (ICAO 2023). This new trend is referred to as urban Air Mobility (UAM) by the industry and academia. UAM is an emerging concept of transportation where small, light-manned and unmanned aircraft operate over small towns and large cities, enabling shorter commute times, avoiding traffic congestion, and facilitating point-to-point flights (Goyal et al. 2019). One of the main applications of UAM is passenger transportation, or air taxis, seeking to reduce traffic congestion in cities while also offering a climate-neutral transportation option for citizens (Uber 2016). Further applications within the UAM market are also considered, and they will be discussed in the state-of-the-art of this work. Innovative concepts with the incorporation of disruptive technologies, such as battery-powered propulsion and distributed electric propulsion, which also include novel aircraft configurations able to take off and land vertically, are pushing forward the development of UAM. Nevertheless, this novel mode of transportation must be a sustainable and emission-free alternative to other transport modes.

Aircraft Design

It is within the tasks of the Chair of Aircraft Design and Aerostructures of the Technical University Berlin to investigate and develop new conceptual design methods for future aircraft generation. These methods should incorporate optimal combinations of technology solutions, which will improve the performance of the aircraft in order to meet the mentioned requirements of the industry and society. The Advanced Morphological Approach (AMA) proposed by Bardenhagen and Rakov aims to be a suitable tool for designers to incorporate and assets innovative technologies for future aircraft concepts (Bardenhagen and Rakov 2019). The AMA works as a tool for creating ideas by suggesting a wider range of possible solutions to a given design problem. It uses the classical Morphological Approach (MA) for generating a wide variety of potential aircraft configurations and handles the lack of quantitative data by using a qualitative evaluation of the technological options (Todorov et al. 2022*a*).

Within the context of the AMA, this work is focused on the creation of one or several Morphological Matrix as a result of the Morphological Analysis and the evaluation of options according to three criteria and represented this in a qualitative scale. Here, characteristics such as functions, subfunctions, and components integration of UAM air vehicles are first identified as system attributes. For each of them, technological options or simple options are proposed based on existing reference aircraft and future concepts for unmanned air vehicles and air taxis. Then, these options are evaluated by using comparing them according to three defined criteria. For this, experimental studies (when found) and literature is used to assess the comparison in a quantitative and qualitative manner. These results are then represented in a common qualitative scale.

It does so by implementing a general Morphological Approach to structure the design of an object (problem) in the context of structural synthesis. Here, the problem is decomposed into attributes that define its functions, subfunctions, and characteristics. Following this, a set of alternative solutions (options) to fulfill each attribute is assigned. Attributes and their corresponding set of options are represented in a matrix called Morphological Matrix. Then, by adding one option per attribute a solution to the design problem is generated Todorov et al. (2022*a*). This method should allow the identification of a vast solution space of configurations for a given design problem, increasing the possibilities of finding the optimal solutions (Todorov et al. 2022*b*).

1.2 Problem

The mentioned environmental goals and challenges, as well as the implementation of a new mobility option in urban environments, justify the design and synthesis of the next generation of aircraft. Most of these designs required a "clean sheet" concept. This starts with the definition of the air vehicle concept in the Conceptual Design Phase. The decisions made during the conceptual design stage have the most significant influences on the project and predetermine the function, form, price, and development of the desired system through its lifecycle (Bardenhagen and Rakov 2019; Sadraey 2020). Additionally, major changes and modifications to the aircraft in further design stages cause delays and extra costs (Todorov et al. 2022*a*). However, it is at this early stage of the design process that the highest number of uncertainties are presented (Bardenhagen and Rakov 2019). These challenges are even more noticeable when disruptive technologies with a lack of experimental data have to be considered (Todorov et al. 2022*b*).

This significant amount of uncertainty is the primary challenge in the conceptual design of novel systems. The searching process is also influenced by psychological factors. Therefore, a person can work with five to seven variable parameters at once. Furthermore, there is an innate human desire to simultaneously vary one parameter while maintaining fixed values for other parameters in order to improve the design solution. However, the number of parameters to consider when looking for configurations can reach hundreds or even thousands (Todorov et al. 2022*a*).

In summary, the conceptual design of future aircraft generations presents challenges of generating a vast number of ideas which include as many potential solutions as possible, as well as the further assessment and comparison of those solutions and technologies with a lack of quantitative data. The multidisciplinary and qualitative character of the Advanced Morphological Approach (AMA) presents a novel concept design method for future and novel aircrafts targeting the mentioned challenges. The goal of this approach is to offer a methodology for systematically identifying a vast, robust solution space, as well as a numerical tool for the systematic synthesis of new aircrafts configurations (Bardenhagen and Rakov 2019). This methodology is well suitable for the development of new aircraft for future aviation markets as Urban Air

Mobility, which is led by novel technologies and aircraft configurations. This requires not only the identification of relevant technologies for the design of such aircraft, but also to consider their integration and implementation. This thesis prepares a use case for the design of future aircraft for Urban Air Mobility for its study with the AMA.

1.3 Aims of the Work

The primary objective of this study is to identify and classify technological solutions related to the conceptual aircraft design for Urban Air Mobility (UAM). In order to achieve this objective, it is required to identify the relevant applications and missions of general-purpose unmanned aerial vehicles (UAVs), as well as those specifically designed for urban air mobility (UAM) purposes. According to this overview, the categorization of the most prominent types of UAVs is primarily based on their respective missions. This will enable the subsequent identification and categorization of key system functions of potential Urban Air Mobility (UAM) vehicles, along with their corresponding definitions as system attributes within one or more morphological matrices. The emphasis during this process will be on identifying innovative solutions to fulfill these attributes.

The second objective involves the development and implementation of quantitative (where applicable) and/or qualitative assessments of chosen technologies, utilizing existing research and literature. To adequately prepare the data for an AMA scenario, it is necessary to convert all assessments, both quantitative and qualitative, into a standardized qualitative evaluation scale.

The main tasks to be completed are defined as follows:

1. Literature research on the following topics1.

   a) The Morphological Analysis and the Advanced Morphological Approach as context of the work

   b) Global UAV applications domains and missions, focus on UAM;

   c) Identification and systematization of promising and existing configurations of UAVs and air taxis as well as their components relevant for conceptual design (focus on unconventional configurations and promising innovative technologies;

   d) Identification or/and derivation of integration possibilities for the technological solutions into the different UAV configurations.

2. Structuring and systematization of the defined UAV components into one or more morphological matrices:

   a) Categorization of the typical UAV types according to the identified mission/application purposes;

   b) Identification of apporpriate UAV system attributes and technological options;

   c)

3. Technology assessment:

   a) Quantitative (when possible) and/or qualitative comparison of selected UAV technologies according to the criteria energy efficiency, emissions and required infrastructure adaptation;

   b) Selection or derivation of appropriate qualitative and/or quantitative evaluation scales;

   c) Transformation of the conducted evaluations into a common qualitative scale.

1.4 Outline

The present work is organized in the following manner: Chapter 1 is the introduction to this work. It includes the context of the work, the problem statement, the aims and goals of this work, and its outline.

Chapter 2 introduces the topics of Urban Air Mobility and Unmanned Aerial Vehicles. Applications and mission requirements considered in market analysis and literature on UAM are presented. This is followed by the key technology enablers, and technical and infrastructure requirements of UAM aircraft to gain an understanding of the evaluation criteria. Furthermore, air vehicles are introduced. The UAS as a system and the global applications of UAVs are defined. Classifications according to their payload and weight classes are introduced. Furthermore, the functionalities of aircraft types are described

In Chapter 3 the theories behind the proposed Advanced Morphological Approach are introduced. This approach is being proposed as a conceptual design methodology, therefore, this chapter starts by describing this design stage. Furthermore, the design task is defined as Structural Synthesis and Parametric Synthesis. The focus of this work relies on the first concept. The AMA uses the Morphological Analysis as a solution to solve the major challenges during the structural synthesis. Therefore the morphological analysis and morphological matrices are explained.

The methodology used to carry out the task of the work is presented in Chapter 4. In this chapter, the approach to categorizing air vehicles according to their mission requirements is explained. Furthermore, the attributes and technological options identification are detailed. In Chapter 5 the results of the categorization of air vehicles according to their most suitable mission are presented. Finally, the results of attribute and technological identification are discussed. The obtained Morphological Matrices are presented in Appendix A.1. The last Chapter 6, is the conclusion. Here, an overview of the work is given. The limitations found during this process to accomplish the tasks of criteria evaluation are discussed. This chapter concludes by outlining the potential for future research and areas that require further investigation.

2 State-of-the-Art

2.1 Urban Air Mobility

This work starts with the most basic understanding of UAM. First, the most relevant applications according to market analysis literature are introduced. This is followed by detailing the requirements of UAM missions for air taxis as a core of the development of the UAM concept. Furthermore, the technical requirements and the technological progress that will enable UAM operations are presented given a justification for the criteria evaluation proposed in the tasks. Finally, UAM infrastructure is introduced along with the most relevant requirements to consider for air vehicles to operate in urban environments.

2.1.1 Market Applications

Urban Air Mobility is still in the early stages of development, with no established uses or missions. Literature on market analysis can help to provide a first insight into UAM applications and justify the demand for the design of new aircraft. The concept of Urban Air Mobility relies on solving traffic congestion in highly dense metropolitan cities by shortening travel time for its users. Also, because of the novelty of this concept, its technological development could offer a solution for reducing emissions in urban environments (EASA 2021). Only considering Europe, UAM could generate a market size of approximately EUR $4,2$ billion by 2030, creating around 90.000 jobs. As well, UAM air vehicles have a backlog of 9400 aircraft for passenger electrical Vertical

Range	Short: under 25km	Long: over 25km	
Durantion	Short: under 20min	Long: over 30min	
Payload Size	Small: under 2kg	Medium Small: 2kg up to 5kg	Large Small: over 5kg

Table 2.1: Drone Deliveries Categorization

and Take-off Landing (eVTOL), and 3300 for cargo drones as for 2022 (Boeck et al. 2023). This corresponds to over 50% and 18% of the aircraft for Future Air Mobility.

Current applications of unmanned aerial vehicles, such as surveillance and infrastructure inspection, can be brought into low urban airspace (Patterson et al. 2018). However, the most addressed use cases for UAM are air taxis, drone delivery, and emergency drones EASA. According to Markets (2023), UAM can be separated into sectors of mobility types: Passenger Transport (air taxis), Freighters Drones (cargo and delivery), and Emergency Services (air ambulance and emergency deliveries). Delivery drones are a niche part of commercial deliveries, however, operations have been growing over the years (McKinsey Center for Future Mobility et al. 2023) and are expected to grow fast by 2030 (MRFR 2020*b*). Use cases, mission ranges and time, and payloads weight found in MRFR (2020*c*,*d*,*a*,*b*) are shown in the table 2.1. UAVs capable of heavier payloads (up to $200kg$) are also under development (Electric VTOL news 2023*b*,*a*).

Passenger operation in urban environments was first introduced with helicopters, nevertheless, this market was never successful due to the performance of the aircraft (Cohen et al. 2021; Voom 2023). This is expected to change with the introduction of novel and really technologies such as Distributed Electric Propulsion (DEP) and Battery Electric Propulsion, allowing for vertical and take-off landing (VTOL) aircraft configurations to decrease noise and pollution. Technical requirements are introduced in the section 2.1.3 of this chapter.

Some market analyses found in the literature are Porsche Consulting (2018, 2021); Goyal et al. (2019); Hasan (2018); Baur et al. (2018), which include different use cases, ranges, and payloads. These are shown in the table 2.2. They all include the air taxi use case, with flight distances from $15km$ up to $113km$ and payloads from

1 to 5 passengers. Airport shuttle services are expected to be the first ones to be offered (Baur et al. 2018) bringing passengers closer to their final destination. The Air metro use case has the payload and ranges similarities with the shuttles, however, it is expected to be a fully scheduled service Hasan (2018). Finally, the Air Ambulance use case is also considered, however, with current battery technology with low energy density makes this market not feasible for fully-electric aircraft Goyal et al. (2019).

Study	Use Case	Range	Payload
Porsche Consulting	Air Taxis	Intracity: 20km to 50km City-to-City: 100km to 400km	N.A.
Rolan and Berger	Air Taxis	15km to 20km, (capable of 30km to 70km)	1 to 2 PAX (+ light luggage)
	Airport Shuttle	15km to 20km, (capable of 30km to 70km)	2 to 4 PAX (+50kg to 80kg luggage)
	Intercity Flights	50km to 250km (Reserve of 50km)	2 to 4 PAX (+20kg to 40kg luggage)
NASA (Booz Allen Team)	Air Taxis	up to 80,5km	1 to 5 PAX
	Airport Shuttle	up to 80,5km	1 to 5 PAX
	Air Ambulance	80,5km to 321km (+ Reserves)	5 to 8 Seats
NASA (McKinsey & Company)	Delivery (Last-Mile)	16km round trips	2,3kg
	Air Taxi	16km to 113km	2 to 5 PAX (454 kg)
	Air Metro	16km to 113km	2 to 5 PAX (454 kg)

Table 2.2: Use Cases found in Market Studies

2.1.2 Mission Requirements

The UAM applications highlighted in the market section suggested that UAM development is mostly focused on the transportation of passengers and goods. The demand for new aircraft is justified; yet, they provide little information on mission requirements. These applications will exhibit different characteristics in terms of flight range, payload mass, and airspeed, hence defining diverse mission kinds. As a previous stage before the design process begins, Top-Level Aircraft Requirements must be established (Torenbeek 2013; Schuh, Spangenberg and Freitag 2021; Sadraey 2020; Raymer 1989; Bardenhagen and Rakov 2019), including the mentioned specifications. Technical requirements play also an important role and they will be discussed further in this chapter. It must be mentioned, that the most popular application concept in UAM is the passenger market (Boeck et al. 2023). Throughout this study, only detailed mission definitions related to this specific sector were identified in the literature.

Within the literature of UAM, several use cases have been defined with corresponding mission requirements Asmer (2021); Patterson et al. (2018); Uber (2022). The same phenomenon is evident in different aircraft sizing studies Silva et al. (2018); Bertram et al. (2022); Nathen (2021); Palaia et al. (2021); Finger et al. (2018). They include the definition of a mission profile dividing the flight process into different stages. The common mission profile for UAM aircraft includes: 1) ground taxi, 2) vertical take-off, 3) transition, 4) climb, 5) cruise, 6) descent, 7) transition, 8) vertical landing, and 9) ground taxi. The aircraft should be also able to fly a reserve mission to an alternate landing place starting from point 2). The examples can be found in the appendix of this document.

A first technical requirement is made obvious, the aircraft must be able to take off, land, and hover in a vertical flight stage. In the case of VTOL aircraft, the duration of time spent in hover and vertical flight mode is a significant factor that must be taken into consideration influencing the choice of an aircraft type and configuration. This phenomenon can be attributed to the significant power consumption observed during the flight mode (Bertram et al. 2022; Palaia et al. 2021; Finger et al. 2018). Therefore, for UAM aircraft TLARs should include the numbers of take-off and landing or the time spent in vertical flight mode (Schuh, Spangenberg and Freitag 2021).

Another requirement is the reserve segment, however, the current reserves established for Instrument Flight Rules (IFR) are essentially equivalent to an additional mission UAM aircraft (Patterson et al. 2018).

The use cases for Urban Air Mobility involve the modification of flight distance and the number of take-offs and landings performed without the need for vehicle recharging. Hence, the mission requirements may exhibit distinct characteristics with respect to the duration of vertical flight conditions, climb, and descent as compared to horizontal flight. (Asmer 2021). The selection of an aircraft configuration is influenced by its distinct performance characteristics that are advantageous for either vertical flight or horizontal flight. Considering the reputation of recognized aerospace organizations such as NASA and the DLR, alongside the popularity of Uber within the UAM community, the use cases and mission requirements are shown in table 2.3. An explanation of every use case is provided in the appendix, and for further details, the cited sources are provided.

Moreover, UAM applications can have different operational concepts, namely on-demand and scheduled operations (Asmer 2021; Patterson et al. 2018). An on-demand mission is representative of air taxis, where the flight route is planned after the user books the flight. For a scheduled operation, the flight route is fixed, and the seats are available until the flight is fully booked. This is the case for air metro services Hasan (2018). These concepts will be used to categorize different UAM aircraft according to the use case.

Source	Use Case	Payload [PAX, kg]	Number of VTOL/ VFL Time [s]	Range [km]	Cruise Speed [km/h]	Reserve [min]	Altitude [ft]
Asmer (2021) Bertram et al. (2022)	Intra-City	$2-4$, 360	3 VTOLs Climb & Descent: 180 Hover & Transition: 360	Total: 50 Single: 17	max. 100	Loiter: 20	N/A
	Mega-City	$4-6$, 540	2 VTOLs Climb & Descent: 120 Hover & Transition: 240	Total: 100 Single: 50	max. 150		
	Airport Shuttle	4, 440	1 VTOLs Climb & Descent: 60 Hover & Transition: 120	30	max. 150		
	Sub-Urban	4, 360		70	max. 150		
	Inter-City	$6-10$, $90kg$ per PAX		< 100	< 100		
Patterson et al. (2018) Silva et al. (2018)	Long-Range Small-Payload	1, 132	2 VTOLs VTOL Climb/Land: 240 Transition: $40s$ Descent: $40s$ Total: 320	Total: 139 Single: $69,5$	Aircraft depended	Loiter: 20	Cruise: 4000 AGL Take-off: 6000 MSL
	Short-Range Large-Payload	$4-6$, 540		Total: $69,5$ Single: 35			
	Long-Range Large-Payload	$4-6$, 540		Total: 139 Single: $69,5$			
Uber (2022)	Sizing Mission	$3-4$, 450	N/A	60	240	$10km$ at $500ft$ AGL	Cruise: 1500 Sizing: 5000
	Repeated Mission		As many as possible $7min$ recharging between landings	25			

Table 2.3: UAM Use Cases with mission requirements

2.1.3 Vehicle Technologies and Requirements

The emergence of urban Air Mobility (UAM) can be attributed to significant technology advancements that have enabled the conceptualization of innovative aircraft capable of meeting the requirements of flying at low altitudes in densely populated metropolitan areas (Uber 2016). The greatest concerns about UAM are the safety of operating these aircraft and the emissions produced by them, including noise and greenhouse gases (GHG) (EASA 2021). Another significant challenge for UAM aircraft is the infrastructure required to operate these vehicles. This includes ground infrastructure for take-off and landing, refueling, maintenance, repair and overhaul (MRO), as well as traffic management infrastructure to ensure safe coordination and navigation. It is also known the importance of cost to make UAM a feasible market. In the context of aircraft design, these requirements are assessed by the technology integrated into the vehicle and the overall concept.

This section only considers UAM passenger aircraft technology since they represent the highest aircraft orders, the greatest investment and innovation in the context of UAM (cite). When looking at some of the most popular aircraft, prototypes, and concepts for UAM (EHang 216, Volocopter, Joby S4, Lilium, Wisk Aero, Midnight by Archer, Vahana and City Airbus by Airbus) they all integrate innovative technologies in the field of propulsion systems and aircraft configurations. As well, these aircraft are expected to develop full autonomy and fly without a pilot. Considering these three fields some of the most popular technologies are introduced.

Propulsion Systems

A great part of the innovation in UAM aircraft can be attributed to the development of technologies in the field of energy storage and propulsion systems with the electrification of the system (Bertram et al. 2022). Electric propulsion is a key enabler of UAM since it addresses the requirements of emissions by enabling the design of ultra-quiet aircraft (Uber 2016) and "zero"-GHG emissions during operation (Bertram et al. 2022). Another important aspect is the low complexity of electric-powered components in comparison to conventional gas turbines (GT) and internal combustion engines (ICE) allowing the reduction of maintenance cost and time (Patterson et al. 2018; Bertram et al. 2022). Nevertheless, the main problem with electrochemical energy sources is their low specific energy and specific power (André 2022).

There is no requirement for UAM aircraft to include any sort of electric propulsion system (Patterson et al. 2018). Energy sources available for UAM aircraft vary from different types of batteries, fossil fuels (kerosene and bio-fuels), hydrogen, and the combination of two energy sources, mainly fuel-electric powertrains, and hydrogen and batteries (Bertram et al. 2022). Electrical energy can be provided continuously by fuel cell systems for higher endurances. This technology uses hydrogen as an energy source and offers an environmentally friendly reaction and noiseless functionality. However, challenges in the cooling system, storage of hydrogen, crash safety, system weight, and limited life service are the main problems in implementing this technology (Kurzweil 2013; Bertram et al. 2022).

By using electric propulsion, power can be distributed over the airframe with relatively few drawbacks in comparison to conventional fossil-fuel-powered systems, This allows for more solutions in the design space, and previous concepts for Short and Vertical Take-off Landing (S/VTOL) can be revised and improved (Patterson et al. 2018). This concept is known as Distributed Electric Propulsion (DEP), and it is the most adopted propulsion architecture by UAM aircraft manufacturers. Implementing distributed propulsion (DP) as a power system architecture means the addition of several motors (normally above 6), speed controllers or gearboxes, and numerous energy storage systems, thus, electric components are the main technology used for DP. Thus, in order to integrate this technology the challenges of aircraft electrification must be addressed first. This multi-component inclusion significantly improves safety by adding redundancy and control robustness (Uber 2016). By integrating DEP into an aircraft further advantages of aero-propulsive concepts can be achieved.

Aircraft Configuration

As it was mentioned, aircraft types will mostly consider the ability to take off and land vertically. The adoption of this concept is to allow as little land utilization as possible, making aircraft able to take off and land in constrained spaces, such as building rooftops. As well, giving the aircraft the ability to hover increases the maneuverability in constrained spaces. However, this capability is more evident in certain aircraft types. When choosing an aircraft type that can VTOL, two options according to lift production during the horizontal flight are able, rotary-wings and fixed-wing aircraft. For this, the definition of the flight mission is significantly important because power output for vertical flight conditions is greater in contrast to horizontal flight (André 2022). Rotary-wing architectures such as helicopters and multi-rotors are favorable for missions where the aircraft is required to perform multiple VTOLs due to their higher hover efficiency. Fixed-wings VTOL have a significantly higher cruise efficiency and speeds making them suitable for longer cruise ranges. Further discussion of aircraft types will be presented in Chapter 2.2.4.

Following the aircraft types, it was already mentioned that DEP allows a greater number of design solutions. In the design of rotorcraft, multiple rotors can be used to produce lift and control the aircraft in contrast to the traditional helicopter. For fixed-wing aircraft, the concept of aero-propulsive coupling comes into play, where the propulsion unit is used to interact with the airframe allowing an enhanced performance and efficiency (Kim et al. 2018). Aero-propulsive advantages will depend on the type of propulsor unit and its position with respect to the airframe. According to Kim et al. (2018) these concepts can be divided into three categories. First, DEP can be used to ingest the boundary layer at the vehicle's wake, increasing the propulsive efficiency and reducing the losses of energy in the fluid. Furthermore, DEP can be used as a lift augmentation system by blowing off surfaces to selectively enhance the dynamic pressure across various aerodynamic surfaces. Finally, the induced drag can be reduced by considering the interactions between wingtip propulsors and the wing's trailing vortex system.

Vehicle Autonomy

The expectation for future UAM operations is to be totally non-dependent on a pilot, neither on board nor on the ground. Remote pilot operations are already a reality for the sector of last-mile deliveries as it was discussed in the market analysis. However, passenger-carrying aircraft for UAM are being developed to first accommodate a pilot on board, and only some companies are focused on bringing the first fully automated aircraft (Ehang and Wisk Aero). Aircraft autonomy aims to enhance safety by avoiding loss of vehicle control and mid-air collisions, autonomous take-off and landing, and system health monitoring (Uber 2016).

NASA expects vehicle autonomy to develop according to a scale of technology maturity named UAM Maturity Level (UML) (Goodrich and Theodore 2021). This scale describes the development of vehicle autonomy in six levels: certification testing and operation demonstration, assistive automation, comprehensive safety assurance automation, collaborative and responsible automated systems, highly integrated automated networks, and system-wide automated optimization. Furthermore, EASA describes vehicle autonomy in three levels AI: Level 1 AI: assistance to humans, Level 2 AI: human/machine collaboration, and Level 3 AI: more autonomous machine (EASA 2023*a*).

Vehicle autonomy will depend on the sensors integrated into the aircraft and the communication network systems with the ground control stations (GCS). The GCS is a main component of UAV operations, and it will be considered as part of the infrastructure required. For design requirements, the aircraft must be constructed with highly reliable sensors to maintain flight attitude, position, and orientation, avoid collision with other air vehicles and urban infrastructure, take-off and land, and monitor the health of systems and components (e.g. engines, battery charge state, etc).

2.1.4 Infrastructure

One of the given criteria to evaluate technological options for UAM aircraft is the required infrastructure modification. Therefore, a basic understanding of the required infrastructure for UAM is provided. This is a crucial requirement for the successful growth of UAM. It includes a ground infrastructure to accommodate passengers, aircraft, and service, and air traffic management to provide communication, navigation, and surveillance (Pons-Prats et al. 2022*a*).

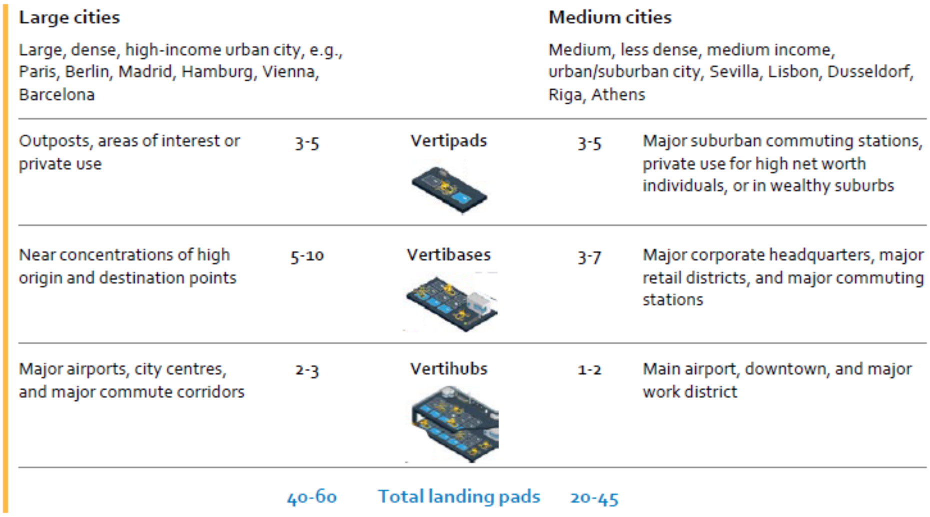

Figure 2.1: Different Vertiports Sizes (EASA 2021)

Ground Infrastructure

Ground-based infrastructure (GI) is characterized for having a small footprint thanks to the ability of VTOL. However, Short Take off and Landing (STOL) fixed-wing aircraft can be adopted in use cases that connect two airports in the same city (Asmer 2021). The landing base for UAM aircraft is named "Vertiport" (EASA 2021). A vertiport can be built with different sizes to accommodate different services for passengers, number of landing pads and take off and landing procedures, MRO services, aircraft refueling (Uber 2016; Pons-Prats et al. 2022*a*; Asmer 2021; EASA 2021). Different sizes of vertiports are shown in figure 2.2 with the number of vertipads, vertibases, and vertihubs depending on the size of the city (large or medium), the location according to the city, and an approximate the total number of landing pads per city. The selection of the vertiport type will mostly depend on the expected traffic volume (EASA 2021). They can be located on top of high-rise buildings, floating barges over water, and roadway cloverleaf (Uber 2016; Fadhil et al. 2018).

The representation of a heliport is used to define the landing area requirements for VTOL aircraft (EASA 2022; Fadhil et al. 2018). A heliport includes three fundamental areas: touch down and lift off (TLOF) area, final approach and take off (FATO), and Safety Area (SA) . TLOF is a circular landing pad providing a designated area for

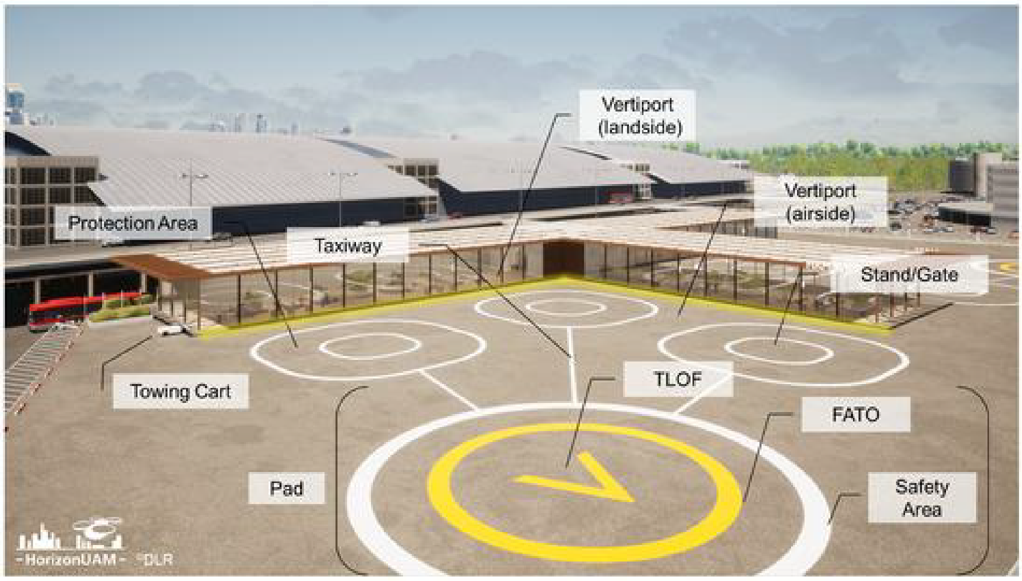

Figure 2.2: Vertiport concept (Schuchardt 2023)

helicopters to land in the center of the helipad. FATO offers a buffer area during helicopter approach or when taking off. The SA is an extra buffer area for ensuring safe operations (Fadhil et al. 2018). According to the cited references, the definition of these areas will depend on the greatest dimension of the aircraft, meaning that smaller and more compact designs are favorable, regardless of the design of the vertiport and the number of landing pads or parking slots. Furthermore, aircraft weight is important to consider the required load that the landing pad must handle (Bauranov and Rakas 2021).

Further technical requirements are under development by EASA (2022). This includes: safety area to perform lateral maneuverings, horizontal clearance to fly above obstacles during take-off and approach, a distance to perform a landing due to a rejected take-off, make sure that the pilot has enough visual angle in the vertical plane (for manned operations) and a protection area for personnel due to downwash effects of the aircraft (EASA 2022). These requirements affirm the importance of aircraft control and maneuverability, as well as the redundancy of propulsion systems in case of failure. Downwash effects resulting because of rotating propellers and rotors as well as wing-induced drag should be reduced to allow safe take-offs and landing procedures of multiple aircraft and ensure personnel safety on the landing pads.

The bigger vertiports must provide refueling infrastructure. The requirements vary greatly depending on the type of energy storage/power source. Most of the literature for UAM is based on battery-powered electrical aircraft Fadhil et al. (2018); Uber (2016). However, the hybridization of the powertrain is considered an option during the first years of operations (Bertram et al. 2022). Furthermore, with the technological improvements in hydrogen storage and fuel cells, this power source will become an option (André 2022; Cwojdziński and Adamski 2014).

Urban Air Traffic Management

It is expected for UAM aircraft to become fully autonomous aircraft. As UAVs, they require a ground control station and a communication data link (Fahlstrom and Gleason 2012). In UAM, these functions will be provided by the air traffic management. Urban Traffic Management (UTM) is a crucial requirement to ensure safe aircraft operation and many concepts are under development (Bauranov and Rakas 2021). The factors that determine the geometry of the airspace regarding the air vehicle are the system's safety, object avoidance, operating under adverse weather conditions and wind gusts, aircraft noise, communication, navigation, and surveillance systems, the dimension of the aircraft, the flight speed, maneuverability and aircraft autonomy (Bauranov and Rakas 2021).

2.2 Unmanned Air Vehicles

This section is dedicated to unmanned air vehicles (UAV) as they are the chosen aircraft for UAM. The main UAM applications were already presented in the previous section of this chapter 2.1.1, 2.1.2. However, one of the tasks of this work is to investigate the global civilian applications of UAVs, as they can also be brought into low urban airspace (Prevot et al. 2016; Thipphavong 2018). To understand the applications, the typical payloads are introduced and a payload-based classification is provided. Furthermore, existing classifications of these aircraft are discussed. Moreover, an understanding of the principal functions of UAV aircraft type is introduced, along with the aspects to be considered for their design. The section is divided as follows: 1) Unmanned Aerial Systems; 2) Civilian Applications; 3) Classifications; and 4) UAV Configurations.

2.2.1 Unmanned Aerial Systems

Unmanned air vehicles or drones are aircraft that do not require an onboard pilot to fly. These air vehicles are remotely piloted or self-piloted to carry a payload to perform a mission, and all flight operations are performed without the need for a human operator onboard. Although the air vehicle is the primary component, it requires a group of coordinated multidisciplinary elements for an airborne mission called Unmanned Aerial Systems (UAS) (Sadraey 2020 p. xlx). The most basic components of a UAS are the air vehicle, its payload, a ground control system, and a communication system/data link. Some types of UAVs might also need the implementation of launch and recovery systems for take-off and landing procedures (Fahlstrom and Gleason 2012 p. 8). A simple description of a UAS is shown in picture 2.3.

For UAM and within the scope of this work, ground control stations and communication data links are part of the infrastructure that the aircraft requires for operating. The most relevant information regarding these systems for UAM was provided in the section 2.1.4. Launch and recovery systems are introduced in the section 2.2.4, as they are dependent on the aircraft type.

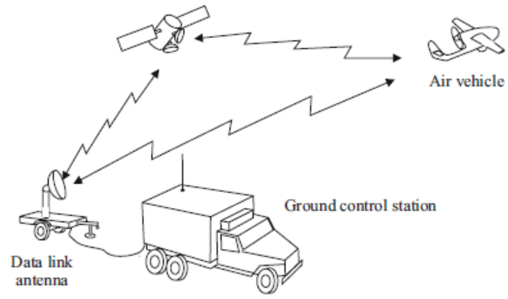

Figure 2.3: Basic Unmanned Aerial System (Fahlstrom and Gleason 2012)

Air Vehicle

As mentioned, the aircraft is the primary system in a UAS, and its design is the focus of this work. Following the definition from Fahlstrom and Gleason (2012), the air vehicle is the airborne part of the UAS, and a basic UAV includes the airframe, propulsion unit, flight controls, and energy source. It is also built with an air data terminal, which is a component of the communications data link. The air vehicle is the platform to transport/carry a specific payload for a given mission. Therefore, the UAV is designed depending on the required payload and its application (Sadraey 2020 p. 483). Small UAVs will be able to carry only one type of payload, but as design sizes increase, the more sophisticated/heavier the payload can be (sensors that require more computational power, or a larger payload mass), even allowing the vehicle to carry multiple payloads during the same flight. The air vehicle can fly and generate lift using a fixed wing or one or more rotary wings. Really unconventional aircraft types are also found such as flapping wings and animal-based UAVs (Hassanalian and Abdelkefi 2017).

Payload

The main reason for deploying an unmanned aerial system is to carry or use a payload. This one is often recognized as a subsystem of the UAS (Fahlstrom and Gleason 2012 p. 9-10). Any equipment or sensor required for normal flight is not considered a payload, and the air vehicle must be able to fly without the payload. This distinction is critical when comparing the useful load capacity of various aircraft types. In UAV design, payload capacity is measured in terms of mass, volume, and power consumption for sensor/equipment operation (Sadraey 2020 p, 482,483). Increasing the power consumption of the payload has the same effect on performance as increasing the payload mass, reducing aircraft range and endurance.

UAV applications are very broad mainly because their payloads are very versatile. They are used to observe the environment or to interact with it (Gundlach 2016 p, 43). Applications based on observing and obtaining information from the environment (surveillance, reconnaissance, search and rescue) employ optical sensors, radars, scanners, and other types of sensors. As a result, this type of payload will be referred to as "sensors" in this work. Packages, containers, and sprayers/spreaders with tanks are used in applications that interact with the environment (delivery, crop spraying). Therefore, there are two sorts of payloads based on how they are used during a mission (Sadraey 2020 p. 483):

(a) **Dispensable:** payloads that will be dropped, delivered, or launched during the mission, such as a package for a delivering mission, seeds, and pesticides for agricultural applications. These types of payloads are transported outside the airframe (in a box, container, or tank) or inside the airframe of the air vehicle. They required a dropping or disposal mechanism.

(b) **Non-dispensable:** payloads, such as sensors and cameras, that will stay onboard the UAV until the flight is over. They are used to observe and collect information about the environment or an object (surveillance, reconnaissance, mapping) (Gundlach 2016 p, 43). The air vehicle can be designed with the payload, or the payload can be mounted in a gimbal. This allows the UAV to be designed with interchangeable payloads, making it possible for the same UAV to be used for different applications.

As the payload defines the usage of the air vehicle, the aircraft will be separated first into their use dependent on the payloads: 1) aerial instruments with non-dispensable payloads; 2) aerial deliveries with cargo dispensable payloads; and 3) aerial sprayers with a sprayer or spreader dispensable (figure 2.4). This excludes passengers as payloads. The reason is that passengers are payloads that require greater mass and volume

Figure 2.4: Applications of UAVs (Prevot et al. 2016)

capacity than the standard drone payloads. Therefore, passengers are considered as another type of payload.

2.2.2 Civilian Applications

The payload choice depends on the application, therefore, payload types were introduced first. In general, UAVs can be employed as aerial instruments, cargo, and aerial dispersers. Although the most popular applications for UAM are passenger and cargo transport, including emergency services, other literature considers the use of UAVs for a wider range of applications (Thipphavong 2018; Prevot et al. 2016; EASA 2021). These potential uses will be comparable to existing commercial and civilian UAV applications since they use the same type of payloads but with stronger safety requirements and the capability to operate in congested airspace (cities with buildings and infrastructures, flying over people).

UAVs are simple to deploy, require minimal maintenance, are mobile, some can hover (Shakhatreh 2019), and are less expensive and safer than manned flight, making them more accessible to people (Gundlach 2016 p. 14). Commercial UAS have a wide range of useful civilian applications in low-altitude airspace. Weather monitoring, public safety, search and rescue, disaster relief, precision agriculture, infrastructure monitoring, and goods delivery are some examples of applications (Prevot et al. 2016). These applications are covered in this section including the required payload, and aircraft types (when provided). However, specific mission requirements are not provided.

Remote Sensing

UAVs in remote sensing applications are used to gather information about an object or area from a considerable distance to observe the earth or a heavenly body (Marshall et al. 2016 p, 23). This includes aerial surveying and mapping using airborne sensors such as cameras, LiDAR, and radars (Gundlach 2016 p, 91). Remote-sensing drones have evolved to various fields of study attracting urban decision-makers to integrate this technology into urban areas such as urban planning (Noor et al. 2018).

Industrial Inspection

Industrial inspection is becoming one of the most relevant applications for UAVs, including several applications within different industries (Marshall et al. 2016 p. 29). Simple payloads such as video and still cameras may be used when visual feedback data is sufficient, however, other missions may require more sophisticated instruments such as LiDARs and hyperspectral imagers (Gundlach 2016 p. 111). Some missions require the air vehicle to fly long-range corridors such as servicing power transmissions, roads, railways, and pipelines (Gundlach 2016 p. 111). For civil infrastructure, small VTOL UAVs can be used for inspecting bridges, radio, cell phone, and other types of towers, preventing humans from falling from great heights. Also, fixed-wing UAVs can be flown to map road conditions and to long-distance transmission powerlines (Marshall et al. 2016 p. 29,30).

Law Enforcement and Public Safety

Intelligence, Surveillance, and Reconnaissance (ISR) and emergency response can be applied to civil and commercial UAVs that are not related to military applications.

Gundlach (2016) refers to these missions as Law Enforcement and Public Safety, where drones could provide surveillance functions to collect real-time, on-demand video (Marshall et al. 2016 p. 35). Small UAVs are probably the most relevant systems, with portable VTOL drones being the most suitable. They could support public services (such as state police) by car chasing, crowd and criminal activity monitoring, traffic control (as speeding cameras), following and monitoring reckless driving, firefighting, border patrol, medical support, and many more (Gundlach 2016 p. 199-223).

Agriculture

Unmanned Aerial Vehicles can support farms and agriculture to enhance production by gathering information about the field, plants, animals and crop, this is called precision agriculture (Marshall et al. 2016 p. 27). Precision agriculture applications include crop management and monitoring, weed detection, irrigation scheduling, disease detection, pesticide spraying, and gathering data from ground sensors (moisture, soil properties, etc.,). Further applications are listed and explained in Shakhatreh (2019) giving examples of the UAVs used and their payloads, which variate from different types of cameras, seed spreaders, and pesticide tanks with sprayers systems (Shakhatreh 2019).

Aerial Filming and Photography

Media and entertainment applications, such as journalism, cinematography, and photography can use aerial platforms with powerful cameras for filming and photography (Gundlach 2016 p. 329). Major news outlets could use UAVs to provide live video reporting of events as they unfold, including traffic reporting and public demonstrations. The FAA approved in 2014 the usage of small UAS in the filmmaking industry being the first commercial application to obtain federation certification (Marshall et al. 2016 p. 33,34).

Traffic and Road Monitoring

UAVs have been thought of as cutting-edge traffic monitoring tools to gather data on the flow of vehicles on roadways. UAVs are more affordable and capable of monitoring large continuous road segments or narrowing down on a specific road section than more conventional monitoring tools like loop detectors, security cameras, and microwave sensors (Shakhatreh 2019). The payloads and vehicle types used found in the literature by Shakhatreh (2019) are VTOL-capable drones carrying cameras.

Logistics and Transport

Logistic and transport missions can range in a variety of sizes, from modest local package delivery services to substantial long-distance unmanned cargo transportation. Use of UAVs over manned aircraft or manned ground transportation may be justified by costs, safety, access, flexibility, or delivery speed (Gundlach 2016 p. 253). Drone deliveries and passenger transport were already discussed in the chapter 2.1 as they represent the most popular applications for UAM. However, some drones capable of lifting heavy payloads can support construction and logistics, by carrying and moving heavy objects to the desired place, such as the VoloDrone (Electric VTOL news 2023*b*).

2.2.3 Classifications

Unmanned aerial vehicles are classified by their performance qualities such as endurance, take-off mass, airspeed, and altitude. A vast number of classifications are provided by Hassanalian and Abdelkefi (2017). However, they are really inconsistent and they do not describe the performance characteristics of some UAM applications. The best example of this is the passenger-carrying UAVs. They could be considered into the heaviest classes, however, they do not meet the performance requirements of the existing classifications (endurance from 3 hours up to weeks Sadraey (2020 p. 6)). A new classification will be proposed based on existing classifications by NATO (Szabolcsi 2016), the U.S. Department of Defense (Fahlstrom and Gleason 2012), and UAV regulations by EASA (EASA 2020*b*, 2019*b*, 2023*b*) and the FAA (FAA 2022).

NATO UAV class is given in table 2.4. The air vehicle is classified by its weight, flight altitude, and data-link range (LOS and BLOS). The terms MALE and HALE correspond to Medium-Altitude Long-Endurance and High-Altitude Long-Endurance, which are drones with flight missions over 20 to 40 hours and 30 to 50 hours respectively. The classification from the U.S. Department of Defense is given in table 2.5. Similarly to the NATO classes, the first parameter for separating the drones in the DoD classes is the take-off mass, followed by the operating altitude and airspeed.

A consideration to make in both classifications is the weight gap within the same group/classe. This is noticeable in group 3 in table 2.5. For example, a fixed-wing UAV of $26kg$ is in the same group as a fixed-wing UAV of $400kg$. Because of the large weight difference, the heavier fixed-wing can have a larger wingspan and heavier propulsion units, outperforming the smaller fixed-wing. Clearly, both drones are designed to meet different TLARs. Therefore, in order to classify drones according to missions, these weight gaps should be reduced.

Weight classifications can also be obtained from federal regulatory agencies such as the FAA and EASA (FAA 2022; EASA 2020*b*, 2019*b*,*a*). UAVs under $25kg$ are considered "small" (FAA 2022). Light UAVs are under $600kg$ MTOM (EASA 2020*b*). And passengers carrying UAM vehicles must be under $3175kg$ (EASA 2019*b*). UAM drones would have to go under certification process, because of these applications being of high risk (EASA 2019*a*). However, certain rules might be derived from the existing regulations (FAA 2023).

2.2.4 Configurations

One of the main tasks of the work is the derivation of systems attributes and technological options for the Morphological Analysis. Integration possibilities of components must be also identified. Therefore, this section of the work explains the main functionalities that each type of aircraft fulfills in order to fly and carry a payload, and the most relevant integration characteristics (such as number and position). Options to fulfill the attributes and integration possibilities are presented in the results of the work and examples for each of these options are provided in the Appendix

The configuration of a UAV and any aircraft is determined by the integration of several components or subsystems to form a complex system. However, the specific components are reliant upon the type of aircraft. Hence, the initial stage is the determination

Class	Category	Normal Operating Altitude	Normal Mission Radius
Class III (>600kg)	Strike/Combat	up to 65.000ft	Unlimited (BLOS)
	HALE	up to 65.000ft	Unlimited (BLOS)
	MALE	up to 45.000ft	Unlimited (BLOS)
Class II (150kg - 600kg)	Tactical	up to 18.000ft	200km (LOS)
Class I (<150kg)	Small	up to 5.000ft AGL	50km (LOS)
	Mini	up to 3.000ft AGL	25km (LOS)
	Small	up to 200ft AGL	5km (LOS)

Table 2.4: NATO UAV Classes

UAS Category	Max. Gross Takeoff Weight	Normal Operating Altitude	Airspeed
Group 1	$\leq$10kg	<1200 AGL	<51m/s (100 knots)
Group 2	>10kg $\leq$25kg	<3.500 AGL	<129m/s (250 knots
Group 3	$\leq$600kg	<18.000 MSL	Any Airspeed
Group 4	>600kg	<18.000 MSL	Any Airspeed
Group 5	>600kg	>18.000 MSL	Any Airspeed

Table 2.5: U.S. Department of Defense UAS Classification System

of the UAV type. There exist several ways of separating these aircraft types (Alghamdi et al. 2021; Hassanalian and Abdelkefi 2017; Fahlstrom and Gleason 2012). However, there are two primary categories that can be distinguished based on their lift generation methods during cruise flight: fixed-wing and rotary-wing (Prajwal et al. 2022; Ugwueze et al. 2023). Furthermore, the importance of VTOL capabilities for UAM divides the category of fixed-wing architecture: CTOL (conventional take-off and landing) and VTOL fixed-wings. Because VTOL fixed-wing architectures integrate the abilities of rotary-wing architectures to fly, hover, and maneuver in a vertical flight condition, the word "Hybrid" is used to refer to these types of aircraft in this work.

By dividing these major groups of aircraft different flight performance characteristics are also noticeable, such as cruise speed, lift-to-drag ratio, and hover efficiency (Bertram et al. 2022), to name some. As explained in the section 2.1.2, the aircraft selection will depend on the TLARs. Moreover, these aircraft types present different methods to function as air vehicles, hence, they require different components. For example, a fixed-wing aircraft requires separate lift and thrust components to produce both forces, while a rotary wing produces thrust with the same component by tilting the vector of the lift force in the desired direction. After the definition of the aircraft, the choice of its configuration and technology systems can follow. An overview of some of the systems and technological options for state-of-the-art UAM aircraft was given in chapter 2.1.3.

Fixed wings

A fixed-wing UAV represents the conventional commercial aircraft architecture and utilizes the same flying concepts (Alghamdi et al. 2021). In comparison to rotary wings and hybrids, fixed-wing aircraft have superior endurance and range due to their high cruise efficiency. Moreover, they have greater payload capacities and fly at higher airspeeds. Their most fundamental components with their primary functions are a wing for lift production; a horizontal tail for longitudinal stability; a vertical tail for lateral stability; a fuselage to integrate payload, avionics, and subsystems; a propulsion system to generate thrust; landing gear to facilitate take-off and landing; control surfaces (ailerons, elevators and rudder) for flight control, payloads, and autopilot for control, guidance, and navigation (Sadraey 2020). These components can be arranged in different positions, quantities, and geometries.

The wing and the horizontal stabilizer can be referred to as a wing system (Gundlach 2014 p. 103), combining lift generation and longitudinal stability (trimming) functions.

Configuration alternatives are similar to manned airplane concepts and include conventional tail-plane, canard, three surfaces, tandem wings, flying-wing, and joined wing surfaces. The wing itself can present different geometries (form, sweep angle, tapper) and positions with respect to the fuselage. Furthermore, the air vehicle can have more than one wing, such as bi-planes and box-wing designs (Gundlach 2014 p. 103-123). Devices for producing higher lift during take-off and landing can be also integrated into the wing, however, they are common only in the biggest aircraft.

UAVs consist most of the time of a single fuselage, followed by blended-wing body designs. The fuselage serves to house several systems (payload, avionics, propulsion systems, fuel), and to connect all major elements. However, the fuselage has a negative impact on the performance, increasing drag and weight. These must be minimized by making the fuselage compact and a low-drag shape (Gundlach 2014 p. 129). The payload might also be integrated in booms under the wings.

Horizontal and vertical stabilizers provide a place to integrated control surfaces for pitch and lateral maneuvers (rudder, elevator). The configuration of the empennage (horizontal and vertical stabilizer) depends on the attachment to the fuselage, either by a single-point attachment or through a twin-boom to the wing. Moreover, the vertical stabilizer can be brought at the tail of the aircraft or as winglets on the wing. (Gundlach 2014 p. 127). The arrangement of the horizontal stabilizer was already considered as the wing system.

The propulsion system can be separated into subsystems: energy storage, engine (power generator), gearbox (optional), and propulsor. The configuration of the propulsion system has several factors to consider. The first choice is the systems architecture: the type and number of engines depending on the power source (gas turbines, internal combustion engines, electric engines). This includes the selection of the propulsor type (open propellers, ducted or shorted fan, fan, etc.). The integration and location of the engines depend greatly on the type of powertrain, the number of propulsors, and the size of the aircraft. A greater source of options will be presented in the results and for further details of how different components and technologies work the cited sources are given: Gundlach (2014); Zhang et al. (2022); Griffis et al. (2009); Cwojdziński and Adamski (2014); Bertram et al. (2022); Townsend et al. (2020).

Various approaches to take-off and landing might be considered based on the size of the aircraft. An alternative approach to defining take-off is the utilization of launch methods. Additional systems, such as a runaway and landing gear, a catapult, or human assistance, will be required. Moreover, the recovery methods primarily encompass various landing techniques, such as parachutes, nets, runways, landing gear, or fuselage supports (Gundlach 2014; Fahlstrom and Gleason 2012; Sadraey 2020).

Rotary wings

A rotary wing or rotorcraft design primarily relies on the lift produced by one or more rotors to sustain flight. A main distinction can be made by the number of rotors, helicopters, and multi-rotors with more than 2 rotors (Ugwueze et al. 2023; Gundlach 2014). Another case is when the rotor is not powered, but generates lift by autorotation with the airflow and a separate engine provides forward thrust (flyargo 2023).

The endurance of rotorcrafts is typically limited as a result of the increased power demand associated with the hovering flight mode (Gundlach 2014; Hassanalian and Abdelkefi 2017). Additionally, the cruise efficiency is lower than fixed-wing airframe and flight range is compromised (Bertram et al. 2022; Asmer 2021). The great advantage is their low disk loading, achieved by large or multiple small rotors. Lowering the disk loading is the main approach to increase hover efficiency, reducing the power consumption during vertical flight (Alghamdi et al. 2021; Asmer 2021). They do not require any type of launch and recovery systems and a landing ski is provided as support for VTOL.

Helicopters

Helicopter or rotorcraft UAVs can vary greatly in their weight and size. They have greater endurance than other VTOL types. Furthermore, they have limited top speed due to the retreating blades. A main problem with helicopters is safety due to a large rotating rotor (Gundlach 2014 p. 47).

The rotor of a helicopter provides three functions: generation of a vertical thrust to overcome weight, generation of a forward thrust for forward flight, and generation of forces and moments to control the attitude and position of the helicopter. Powering the rotor is accompanied by a torque that must be compensated. The configuration of the helicopter is given by the arrangement of the rotor and the method to balance torque. This is done by using a single main rotor (SMR) and a tail rotor (torque balance system) or two contra-rotating rotors (CRR) (Johnson 2013 p. 1-7).

Flight control of a helicopter is also reliant on the configuration. The general approach to maneuver and control the aircraft is by changing the pitch angle of the rotor(s) blades symmetrically (collective) or asymmetrically (cyclic). However, in an SMR the yaw control is provided by the torque balance system. The main rotor itself is responsible for the provision of pitch, roll, and vertical control, and when including two rotors, also for yaw control (Johnson 2013 p. 276-278). The attachment of the rotor to the fuselage is another important aspect of the design. The rotor hub must be able to sustain loads of the blade motion (Johnson 2013 p. 271-275). Furthermore, the geometry of the blade must be also considered.

Aerodynamic surfaces for longitudinal and vertical stability are also integrated (horizontal and vertical stabilizer/fin) in different arrangements with control surfaces. Furthermore, helicopters can also possess a wing to generate lift during cruise flight or a propulsion system for forward thrust. This is known as a compound configuration and it can be referred to as lift-compounding and thrust-compounding. Adding a wing, a forward propulsor, or both aims to enhance performance (airspeed, lift-to-drag ratio, and flight control) (Maurya et al. 2021; Leishman 2000).

Multitorors

Multirotors (MR) or multicopters have a large share of the small UAV market and their technology has matured enough to provide man-carrying applications (Finger et al. 2017). They main characteristics

However, increasing the aircraft size is done primarily by adding more rotors, rather than increasing the rotor size (Finger et al. 2017). The layout of a multirotor includes the fuselage in the middle, and the rotors mounted on arms symmetrically around it. MR configurations are derived mainly from the number of rotors (quadcopter has four rotors, hexacopter has six rotors, etc.) and their arrangement (isolated or coaxial) (Finger et al. 2017).

Despite the similarities in general flight mechanics between helicopters and MR, the latter present a notably relatively simple control system. As rotorcrafts, they have to balance the torque produced by the rotors. The vast majority of MR have an even number of rotors, and they cancel torque by spinning half of them clockwise and the other half counter-clockwise. In contrast to helicopters, they tend to have fixed-pitch rotors, and aircraft control is achieved by changing the rotational speed (RPM control). This characteristic makes MR the simplest because they can be controlled only by the motors and no other actuator systems are required. However, to maintain this simplicity, electrically driven motors are required (Gundlach 2014 p. 472-474). Moreover, in order to maintain the simplicity of operating this type of aircraft, automatic flight controllers must be integrated (Finger et al. 2017).

Hybrids

Hybrid configurations function as fixed-wing aircraft during horizontal flight and climb, and they possess the ability to hover and fly vertically as multirotors. They are similar to fixed-wing airframes and wing system configurations are almost the same. Flight control schemes in vertical flight are similar to multirotors, while in horizontal flight the aircraft is controlled as a fixed-wing (Finger et al. 2017).

The fundamental characteristic of hybrids is the method by which they combine the ability to fly vertically and horizontally, followed by the method for transitioning from one flight condition to the other (Finger et al. 2017). Essentially, the thrust vector must be provided in the direction of the aircraft's current flight condition. Therefore, the propulsion system works as a "lift + thrust unit" (LTU) by providing vertical lift and forward thrust (Ugwueze et al. 2023; EASA 2019*b*). This is achieved by (Finger et al. 2017; Ugwueze et al. 2023): 1) adding independent LTUs, one for vertical lift and one for forward thrust ("lift + cruise"); 2) using the same LTUs by changing the vector of the thrust (thrust vectoring); and 3) a combination of both.

The lift + cruise (LC) is a less complex configuration since it does not require any mechanism to change the thrust vector, and flight transition occurs by starting the forward thrust unit, providing horizontal flight speed for the wing to generate lift (Finger et al. 2017). Changing the thrust vector can be done by: 1) tilting the propulsor or engines (tilt-rotor), 2) tilting the wing, part of the wing, or horizontal stabilizer (tilt-wing), 3) tilting the whole aircraft (tail-sitter or tilt-body). Combinations of 1) and 2) are also possible.

Aircraft control during every flight state must be provided. In general, hybrids have the same flight mechanics requirements as fixed-wing during cruise flight, and as multirotors during vertical flight. The addition of thrust vectoring can provide another mechanism for flight maneuvers. The most critical stage is the transition flight Hybrids vary greatly in their configuration, and one could argue that each configuration might be another type of aircraft. The most fundamental characteristic is the method they combine the ability to fly vertically and horizontally (Finger et al. 2017), which also defines the way the transition between these two flight conditions. This is done by the thrust unit, and because it is used as lift-producing device during vertical flight phases, it is named the "lift + thrust" unit (Ugwueze et al. 2023; EASA 2019*b*). At the most general categorization, three basic methods are proposed (Finger et al. 2017): 1) additional propulsion unit ("lift + cruise); 2) using the same propulsion unit (lift = thrust); and 3) they required one or two systems to provide the aircraft with an upright force during vertical flight, and Several approaches have been proposed to classify them ()The first characteristic to differentiates these aircraft is the transition method and the installation of different propulsion units to provide lift during vertical flight and thrust during horizontal flight. This combination of lift and thrust is named "lift + thrust" unit.

3 Theoretical Background

3.1 Conceptual Design

The current work follows the fundamentals of the Advanced Morphological Approach, a novel method proposed by Bardenhagen and Rakov to address the conceptual design of Engineering Solutions (ES) such as aircraft. As a conceptual design methodology, the principles behind this design phase must be understood.

From the standpoint of synthesis, the design of a system is structured through conceptual, preliminary, and detailed design. The first and most important phase of the development process and design of a system is the conceptual design phase. This early stage of the process has a high level of influence and the potential to establish, commit, and otherwise predetermine the function, form, price, and development of the desired system through its lifecycle (Sadraey 2012 p.23). Bardenhagen and Rakov (2019) also highlight the conceptual design phase of an aircraft as the most challenging stage. During the concept design, a high number of complex decisions regarding the aircraft components and their arrangement into a structure have to be made with a long-term and irreversible impact (Bardenhagen and Rakov 2019).

Starting a design project must be justified. In the phase of the conceptual design, a valid justification is provided by the identification of a problem and associated definition of need (Sadraey 2020 p. 21). This is represented by a particular set of design requirements established by the prospective consumer or a company-generated guess as to what future customers may desire (Raymer 1989 p. 7). In this context, these requirements are the problem to solve during the design process and the designed system must fulfill them. During the conceptual design stage, a document of top technical requirements which include the specifications of the system is developed in order to offer overall guidance from the start of the design process (Sadraey 2020 p. 21). In aircraft design, this is usually found as "Top-Level Aircraft Requirements" or TLARs. Typical requirements include range and payload, takeoff and landing distances, maneuverability, and speed requirements (Raymer 2018 p. 7). UAM mission, technical, and infrastructure requirements relevant to establishing TLARs for the conceptual design of passenger carrying can be derived from sections 2.1.2,2.1.3,2.1.4. As the name states, this stage is the process of the design at the concept level, where an initial and viable configuration is generated (Sadraey 2020 p. 22), which represents the general layout, dimensions, external shape, technologies, and other characteristics (Torenbeek 1982). For this, the designer's principal tool is the "selection" (Sadraey 2020 p.22-23) of the type of aircraft, the arrangement and position of the components, and the principal technologies to be included, Therefore, this stage is a highly creative and imaginative process, where brainstorming sessions are arranged to generate "novel and wonderful ideas" (Torenbeek 1982, 2013). However, brainstorming one or many feasible concepts requires great experience from the aircraft designer (Sadraey 2020 p. 22), as well as being fully aware of the state-of-the-art technology and its future development (Raymer 1989 p. 7). Finally, the selection of components and technologies is based on a trade-off analysis by comparing all pros and cons in conjunction with other components (Sadraey 2020 p. 23).

The main goal of this phase is to acquire the information required to decide if the concept will be technically feasible and economically profitable (Torenbeek 1982 p. 5). Conceptual design is an iterative process, where the primary components are sized provisionally to generate a baseline design. If the requirements are not met, or if enhancements to performance are sought, the process can be repeated from an earlier specification level depending on where the modifications are desired, in order to obtain the most optimal design. However, defining the most optimal design as the baseline is not always possible due to the application of active constraints (Torenbeek 2013 p. 11).

In the case of innovative solutions, this problem is greatly intensified as it was mentioned in the problem statement of this work. The assessment of a novel aircraft conceptual design will rely to a certain extent on limited empirical data and basic mathematical models. Therefore, the obtained "most optimal" baseline concept will undergo frequent modifications over time and may possibly be too simplistic to justify further comprehensive analysis (Torenbeek 2013 p. 11). In this case, a set of various solutions to reach the desired goal will be provided (Torenbeek 1982 p. 7), therefore Todorov et al. (2022*a*) proposed to not seek optimal variants but rather synthesize a certain number of reasonable solutions that are close to the theoretical best based on the given requirements (Todorov et al. 2022*a*).

The Conceptual Design of a UAV

> *"UAVs are air vehicles, they fly like airplanes and operate in an airplane environment. They are designed like air vehicles. They have to meet flight critical air vehicle requirements. You need to know how to integrate complex, multi-disciplinary systems. You need to understand the environment, the requirements and the design challenges"* (Sadraey 2020 p. 3).

When it comes to the design of a UAV, the design principles are similar to the principles developed over time and effectively used in the design of manned UAVs (Sadraey 2020 p. 3). As mentioned in the previous section of this chapter, the main goal during the conceptual design phase is to deliver a design solution with the arrangement of the UAV components and the technologies to be integrated into it, named a configuration. This process should start with the definition of the UAV type and its configuration.

Different types of UAVs and their most relevant functions were presented in chapter 2.2.4. A UAV is a system comprised of several major components (Sadraey 2020 p. 23), and each component can be a system of its own (Schuh, Spangenberg and Freitag 2021). Every UAV element is interconnected with other components and can interfere with their functions. Schuh, Spangenberg and Freitag (2021) "disassembled" the system of a UAM aircraft in its top-level basic components: Lift, Thrust, Energy Storage, Power Provision, Flight Control, Aerodynamic Contour, Structure, Interior, Systems, and Landing Gear. Following the definition of components and functions, several alternatives of technologies and component arrangement are brainstormed accordingly to the aircraft type.

3.2 Advanced Morphological Approach

Within the AMA context, the current work is focused on the early stages of this method, mainly the creation of Morphological Matrices (MM) and the evaluation of a given set of criteria. MMs are a fundamental element of the Morphological Analysis (MA) which is used in the AMA in the context of structural Synthesis to expand the space of possible solutions for the design of a system under a given set of Top-Level Requirements (TLR). The design space generated with the AMA relies on the integration of innovative technologies into the system and handles the lack of quantitative and statistical data by evaluating each option in a qualitative matter. The result of the AMA is not only one optimal solution but a detailed exploration of the solution space is provided. Further theories behind the AMA include system and cluster analysis. Although this work is focused on the design of aircraft, AMA can be implemented in the structural synthesis of other Engineering Solutions (ES) and domains (Bardenhagen and Rakov 2019; Todorov et al. 2022*a*).

Detailing the complete AMA is out of the scope of this work and only the stages of this design are presented according to Bardenhagen and Rakov (2019); Todorov et al. (2022*a*,*b*). AMA can be summarized in the following stages: 1) Problem statement definition: the definition of TLARs for aircraft design problems. 2) Synthesis of the MM, 3) Definition of system criteria, 4) Evaluation of technological options: in the MM technical options are given to each of the system's attributes. These are further compared and evaluated according to a defined set of criteria using a qualitative scale from 1 to 9 (worst to best option). Experts' opinions are sought for technological options with a lack of performance information. 5) Reference solution selection: A handful of current solutions (aircraft) that meet the TLR are chosen for further research. These are decomposed according to the morphological matrix and rated based on their integrated technical option. 6) Solution space generation; 7) Clustering: Groups of similar aircraft configurations in the generated solution space are clustered. The procedure employs distance metrics such as the Hamming distance, which equals the number of technical possibilities in their attributes. 8) Solution analysis and selection 9) Prediction model synthesis, parametric modeling, and optimization stage.

The current work is focused on the stages 2) and 4). The given set of criteria is

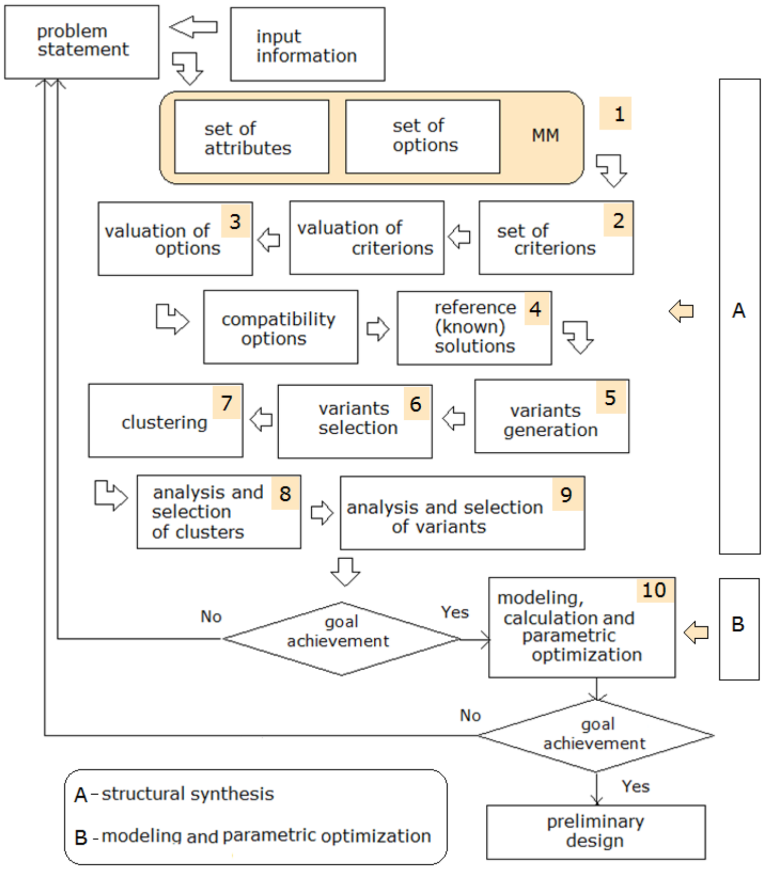

Figure 3.1: AMA block diagram (Bardenhagen and Rakov 2019)

provided in the task of this work. Therefore, the further sections of this chapter are focused on the theories of structural analysis and the MA.

3.2.1 Structural and Parametric Synthesis

The conceptual design phase of an Engineering Solution (ES) - a system, object, or process - can be broken down into two major tasks (figure 3.2): a) structural synthesis and b) parametric synthesis (Bardenhagen and Rakov 2019).Structural synthesis refers to the process of designing and creating structures, systems, or objects by systematically combining and arranging different components or elements in a way that meets specific functional requirements and objectives. Moreover, parametric synthesis is a

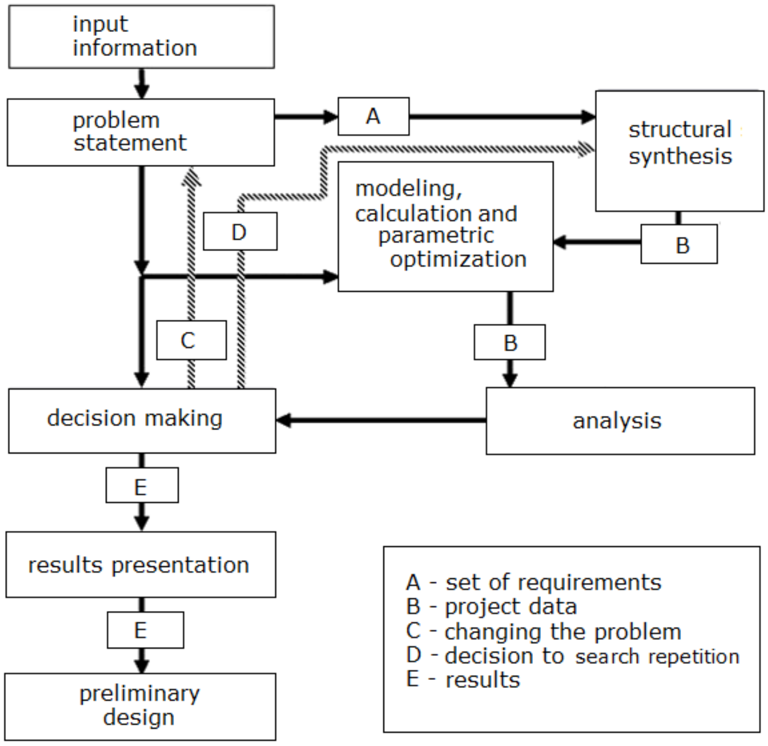

Figure 3.2: Design Process (Bardenhagen and Rakov 2019)

design approach that involves creating variations of a design by altering specific parameters or variables within a predefined set of rules or constraints. The methods used for addressing these two challenges are vastly different (Rakov 1996; Bardenhagen and Rakov 2019). In general, parametric synthesis, utilizes approaches that satisfy the metric criteria making the problem formally solvable. Design alternatives can be generated, evaluated, and optimized through computational processes. However, the task of structural synthesis is entirely different as it cannot be classified as a problem that can be formally solvable (Todorov et al. 2022*a*) through formal, algorithmic, or mathematical methods. In the context of the AMA, the presented work is based on part of the structural synthesis. "*The structural synthesis result is the choice of the rational structure of the object.*" (Bardenhagen and Rakov 2019). This is not a trivial process for highly complex systems. Developing a system's structure requires dealing with uncertain structural connections due to the complexity of integrating various components, materials, and systems. In addition, some elements of the structure possess non-metrical attributes (non-quantifiable properties). Furthermore, the synthesized structure and its integrated elements must satisfy quality criteria to guarantee functionality, durability, and safety (Rakov 1996; Bardenhagen and Rakov 2019).

When designing an ES, there is a desire to optimize certain objective functions to improve the design solution, such as reducing the system's weight, pollution, cost, etc. However, the requirements of usual optimization methods do not correspond to the objective function of structural synthesis (Rakov 1996; Bardenhagen and Rakov 2019). The optimization and further synthesis, because: 1) it might have abrupt changes (discontinuous); 2) it might not always provide a clear solution (indeterminate); 3) it involves complex operator notation; 4) it is not based on analytical expressions; 5) it is not differentiable, not unimodal, not separable and not additive (Todorov et al. 2022*b*).

The primary challenge associated with the conceptual design of innovative ES relates to the significant magnitude of information uncertainty. Psychological factors also influence the search process. An individual has the capacity to concurrently manipulate and analyze a range of 5 to 7 variable parameters. Furthermore, individuals possess an innate inclination to enhance the design solution by concurrently manipulating one parameter while keeping the values of others constant. However, the number of parameters involved in the search for configurations ranges from tens to hundreds (Todorov et al. 2022*a*).

3.2.2 Morphological Analysis

The definition of Morphological Analysis is not trivial (Garvey 2016 p. 81). "Morphology" refers to the study of form, and "analysis" means breaking down an object into its constituent parts and the relationship of these parts when examining the whole (Garvey 2016 p. 84). Therefore, morphological analysis can be understood as a method for the study of the form of an entity (in this case, a system) by decomposing it into its individual components and the relationship between these as a complete structure. Its development and first implementation as a technique are attributed to the Swiss astrophysicist Fritz Zwicky, who developed the method through the 1950s and 1960s

(Garvey 2016 p. 87). It was developed as a problem-structuring approach to explore all possible solutions that could be found for problems that are multi-dimensional, multi-criteria, and non-quantifiable, involving a degree of uncertainty (Todorov et al. 2022*a*). This not only allows to produce a vast number of ideas to solve the problem but also enables a further detailed analysis by identifying the multi-variable structural components of the problem. Nevertheless, it is the ability to generate a great number of possible solutions that presents a major problem when using this method (Garvey 2016 p. 82).

The explanation and definition of the MA are given in an "informal" manner by Garvey in order to facilitate its comprehension. He broke down the definition of MA from one into a number of linked statements. In theory, this method works as follows (Garvey 2016 p.104-105):

- The MA enables the identification of informed and innovative solutions for complex problems with high levels of interconnectivity and uncertainty..
- As a technique for generating ideas, it breaks down unstructured ideas and concepts into a group of modular components that may be utilized to create novel and creative "products" or concepts. Furthermore, by structuring the problem, inconsistent relationships inside the problem boundary are eliminated, leading to a significantly smaller set of viable solutions. This procedure reduces the risk of making the wrong decision due to the level of uncertainty.
- As a result, rather than obtaining only one possible solution, this reduced set of viable options incorporates multiple concepts to deal with uncertainties and new phenomena.
- In summary, the MA reduces the risk of events occurring unexpectedly (by mitigating negative unintended consequences), while identifying innovative opportunities that would not have been considered (positive unintended consequences).

The morphological method or analysis has been proven to be effectively implemented in the structural synthesis of a system to address its challenges (Rakov and Timoshina 2010; Todorov et al. 2022*a*). It is the most frequently used method to search and synthesize engineering solutions, including structural synthesis for the realization of scientific ideas (Bardenhagen and Rakov 2019). The problem in structural synthesis and conceptual design is the design of an engineering solution according to a given set of requirements. When considering the mentioned theoretical explanation of the MA by Garvey, in the context of the design of a concept, Todorov et al. give an explanation of the method in three parts, 1) decomposing and structuring the problem into a Morphological Matrix (MM), 2) identifying and eliminating impossible solutions by a Cross-consistency Assessment through a Cross-consistency Matrix (CCM), and 3) the generation of a viable solution space by substracting the CCM from the MM.

However, the core of this work in the context of the MA is the creation of MM. Therefore, further discussion of the Cross-consistency Assessment and the Solution Space Generation is not provided, and they were only mentioned to give an understanding of how the method is applied. The MA uses MM to handle the synthesis of a technical system by first breaking it down into its simpler characteristics or functionalities that must be fulfilled. These are further assigned in a Morphological Matrix as attributes, and their total number quantifies the dimension of the problem. For each of them, options and alternatives that can satisfy the corresponding attribute are found and assigned. For one attribute only one option can be selected, and the combination of options for the same attribute is not possible. Engineering solutions frequently incorporate technological options, but these may also include operational and other aspects such as systems integration. Finally, attributes and options are grouped into a matrix (Todorov et al. 2022*a*). A generic MM is shown in figure 3.3.

3.3 Measurement Scale

3.3.1 Energy Efficiency Parameters

The evaluation of technological options for a selected set of attributes, the results from both quantitative and qualitative evaluations must be transformed to the same scale. This requires the proposed scale to be unitless because the chosen criteria, their evaluation parameters, and their qualities do not always possess the same unit.

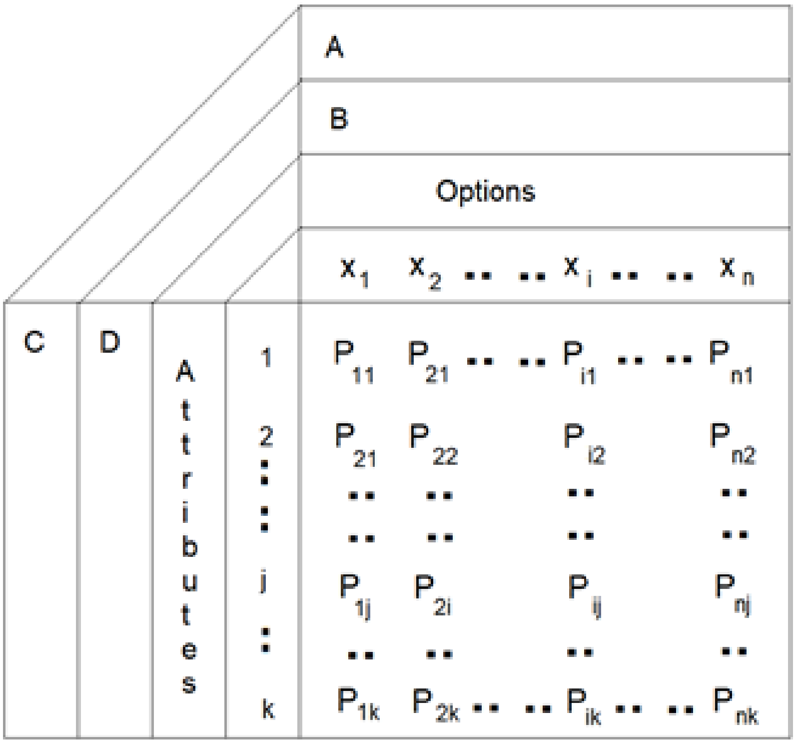

Figure 3.3: Generic Morphological Matrix as found in Todorov et al.

This requirement of a unitless scale can be achieved through Normalization Methods (NM). Normalization is a scaling method that is employed to make criteria comparable by removing the influence of optimization direction (such as beneficial or cost criteria), the unit of measurement, and the range of variation (Aytekin 2021). These techniques are commonly used in Multi-Criteria Decision Making (MCDM) methods. The theory of MCDM can be utilized to solve the evaluation task given in this work by evaluating and ranking a number of options in order to identify the most optimal alternatives that effectively fulfill a specified set of criteria. Thus, NM enables the aggregate of the criteria into a final score. Therefore, the problem of transforming quantitative parameters with different units is solved. Another aspect of NMs is that they also allow the transformation of qualitative input data into numerical and comparable data (Vafaei et al. 2016).

Different NM exist (Vafaei et al. 2016; Aytekin 2021). However, following the proposed scale by the AMA (chapter 3.2), an NM that allows the assignation of a worst and best alternative is chosen. Thus, the NM selected as a scaling method is the Maximum-Minimum Linearization Technique. The approach takes into account both the maximum and minimum values of attribute performance ratings during the calculation process.

Furthermore, a beneficial attribute or criterion implies that as performance improves, so does the ranking. The opposite is true for cost or non-beneficial criteria, the lower the value, the lower the ranking (Çelen 2014; Vafaei et al. 2016; Aytekin 2021). For a given criterion there exist two or more options, and a maximum n_{max} and minimum value n_{min}. A given option has the value n_ij for a given criterion. For beneficial criteria, the ranking r_{ij} of the option n_ij is given by:

$$r_{ij} = \frac{n_{ij} - n_{min}}{n_{max} - n_{min}}, \tag{3.1}$$

and for cost criteria the ranking r_{ij} of the option n_ij is given by:

$$r_{ij} = \frac{n_{max} - n_{ij}}{n_{max} - n_{min}}. \tag{3.2}$$

The obtained ranking value is in the interval $[0, 1]$. The most optimal alternative obtains a ranking of 1 and the worst alternative a ranking of 0. The advantages of Max-Min NM are its simplicity and that the relationships between options are preserved. However, if there are outliers in the dataset that have values much higher or lower than the majority of the data, these outliers can disproportionately influence the range of the scaled values.

3.3.2 Qualitative Rating Scale

In this work two types of data must be used, quantitative and qualitative. Quantitative data are numbers used to define information that can be counted. In the context of this work, some examples are energy efficiency degrees, lift-to-drag ratios, thrust-to-power ratios, etc. Qualitative data are information about the qualities of an object, or information that cannot be quantified.

A relative ranking scale is generated by using a Max-Min normalization technique. It is a relative scale because it compares a given value to a reference value (Kamat 2019). In the case of Max-Min. NM, this reference value is the distance between the maximal and lowest performance. However, the ranking score remains in the $[0, 1]$ interval. Todorov et al. (2022*b*) proposed a scale with the interval $[1, 9]$. The Max-Min NM is a linear normalization method. Thus, the original interval could be expanded with a linear function, maintaining the order a dimension of the rankings.

4 Methodology

To solve the tasks and aims of the work, the methodology followed a clear path. 1) Literature research was carried out in order to gain theoretical background on the topics of Unmanned Aerial Vehicles, Urban Air Mobility, the Advanced Morphological Approach, and Morphological Analysis. This allowed the identification of aircraft types, mission and technological requirements, and infrastructure requirements. 2) A global UAV classification was derived based on common UAV classes in order to categorize air vehicles according to their most suitable mission requirements. The specification of reference existing UAVs was collected, and the air vehicles were sorted according to the global UAV class and their applications according to their type of payload. Following this, TLARs for UAM missions were proposed, and the most suitable aircraft type was assigned according to these findings. 3) The functionalities and main components of the air vehicles were identified in the literature, and the UAV system was decomposed into its main attributes using the MA. Based on the technology requirements, the collected reference UAVs, future air taxi concepts, technological options, and component integration possibilities were identified.

The literature research was already presented as the state-of-the-art and the theoretical background of this work (Chapters 2 and 3). This chapter is structured as follows: 1) first the method behind the classification is discussed; 2) this is followed by the attributes and technology identification, including the derivation of the morphological matrixes; 4) and finally the approach for the criteria evaluation and the transformation to a common qualitative scale is introduced.

4.1 Classification

4.1.1 UAV Classes

In chapter 2.2.3 two classifications of UAVs were presented according to NATO and U.S. DoD (2.4 and 2.5). They were chosen for two reasons:

1. They include all UAV configurations without classifying VTOL aircraft as a separate class. This is necessary in order to determine which aircraft configurations are better suited for specific applications based on their performance.

2. They share similarities in classifying UAVs based on their mass, allowing a simple way to identify technology and performance trends between aircraft of similar sizes

However, as mentioned in subchapter 2.2.3 the weight gaps should be reduced. Therefore, both classifications were merged into one. From the smallest weight class to the heaviest, the proposed classification is built with Groups 1 and 2 of table 2.5, followed by the rest of NATO Class I (above 25kg up to 150k), Class II of table 2.4, and the heaviest class above 600kg. Group 2 of D.o.D is chosen as an upper limit for small UAVs because it aligns with the weight limits for regulations mentioned in chapter 2.2.3. For UAVs in NATO Class II, EASA special condition for Light Unmanned Aircraft Systems applies (EASA 2020*b*).

The sorting of the UAVs into classes is made according to the weight, and the rest of the parameters airspeed, operating altitude, and endurance are not considered. Three assumptions are made for this. 1) UAM operations are expected to occur in low airspace (Prevot et al. 2016), and all aircraft types will have to operate at similar altitudes. Therefore operating altitude is not taken into account for the proposed classification. However, it is an important parameter for aircraft sizing methods. 2) airspeed is not considered because the classification includes different aircraft configurations, and their airspeed characteristics differ. 3) The last assumption is to exclude the terms HALE, MALE, Tactical, Strike/Combat which are derived from military applications. Endurance and Range for each class will be derived after gathering information on existing UAVs, which is the next step taken in this methodology. The proposed classification will be presented in the chapter 5.1.

4.1.2 Air Vehicle Categorization

In order to classify non-carrying passenger air vehicles according to their most suitable applications, several existing commercial UAVs were investigated. Information about their performance was gathered from the manufacturer's website or global UAV seller websites. The goal of this methodology was to find trends in how aircraft configuration affects their performance and the payload that they can carry for a given mission. Thus, information about take-off mass, payload mass, flight endurance, range, airspeed, and payload type was obtained.

The next step was to assign the UAVs according to their payload type and applications as aerial instruments, cargo drones, and aerial dispersers (chapter 2.2.1). If a UAV is capable of carrying two different payload types (e.g., cargo and/or sensors), it is assigned to each category. Following this, the UAVs were sorted into the proposed weight classification according to their MTOM. The influence on performance due to different energy sources and aircraft dimensions is also considered. The effects of increasing aircraft dimensions are discussed; however, no graphic is provided showing these effects. The reader can find the complete list of the air vehicles in the appendix **??** to confirm these facts.

The major problem with this methodology is the lack of data provided by the manufacturers. Thus, several UAVs could not be considered and were left out of this list because of the missing information (no payload mass or take-off mass, endurance, etc.). This problem is even intensified for passenger-carrying air vehicles, and it could not be applied. Moreover, the weight of the fuel system and empty weight were barely specified, so they were not considered. However, in some cases, the maximum payload and endurance will vary for the same UAV due to heavier batteries, fuel mass, or engines (e.g.,Acecore; **?**). In these situations, the UAV was listed for each of the different specifications.

Furthermore, the data given by different manufacturers is not consistent. For some air vehicles, not only the maximum values were given. Some of them (e.g., Wingcopter) specify the range and endurance that the drone can fly with a given payload and take-off mass (heavier payload, less endurance). Gathering the specific payload mass, take-off mass, and cruise airspeed for a corresponding flight endurance or range could have allowed a more precise analysis. However, this was not possible for the majority of the UAVs. Therefore, only the maximum performance data is taken. Nevertheless, the cruise speed was considered over the maximum airspeed if it was specified. In most of the cases, endurance was specified instead of range. Therefore, the range was computed by multiplying the airspeed with the given endurance. This takes into account the assumption that the aircraft can fly the endurance mission at a constant speed and that take-off and landing procedures do not affect aircraft range.

The most suitable aircraft types are proposed for each mission. The recommended aircraft for passenger transportation is based on the number of VTOLs, hover time, and cruise range. For cargo drones, air vehicle recommendations are based on the gathered performance information. According to the performance specifications of reference cargo UAVs, suitable use cases are presented. The author recommends aircraft types, including the energy storage option, based on endurance, payload, and airspeed identified for each UAV weight class. However, for a specific mission, the author only recommends the lighter UAV weight class suitable to perform the mission's TLARs, leaving the aircraft type to the designer's preference.

4.1.3 UAM Missions

The literature research for global UAV civilian applications was presented in Chapter 2.2.2. Despite the fact that these applications are well suited to urban environments, the UAM applications chosen are based on the market analysis literature introduced in chapter 2.1.1.

Use cases and missions TLARs for passenger-carrying missions were identified in the literature and introduced in chapter 2.1.2. The major applications were grouped together, taking into account their similar proposed requirements and operational concepts (on-demand or scheduled). TLARs are proposed for each of the use cases by specifying total range and single leg range (without refueling), number of take-offs and landings with total minimum hover time, number of passengers and weight allowed per passenger (to consider the luggage), as well as recommended qualitative airspeeds.

The applications and missions in the freighter sector are determined based on the performance and payload capabilities corresponding to each weight class of UAVs, as discussed in the previous section of this chapter. Emergency use cases exhibit similar requirements to the other two sectors within the UAM domains. Consequently, they were incorporated into both prior UAM applications.

4.2 Morphological Analysis

4.2.1 System Attributes Identification

The principal functionalities and component integration possibilities of each type of aircraft were found in the literature and presented in chapter 2.2.4. As explained in chapter 3.2.2, the UAV is decomposed into its system functionalities and these are represented as attributes in an MM. The reference vehicles gathered in the previous step of the methodology (chapter 4.1.1) were used to find further attributes, such as payload integration, payload deployment, etc. A list of the attributes with their corresponding functionalities is provided in the appendix **??**.

In order to reduce the result of non-compatible systems, attributes that have a high degree of dependency on the choice of a specific component from another attribute were merged into one attribute. For example, the selection of the powertrain architecture and engines depends on the selection of an energy source. Furthermore, there are functionalities with a high degree of interaction. A clear example is lift production with a rotary wing that must be coupled with a torque balance system or method in the case of rotorcraft. These two functions could be represented by the same attribute.

4.2.2 Technological Options Identification

From the UAM literature presented in chapter 2.1.3, some of the most relevant technologies were found and assigned to their corresponding attribute. Furthermore, by collecting information on reference aircraft, several technology options integrated into them could be selected. Although performance data from future air taxi concepts was not gathered, different options for system attributes could be identified and assigned to their corresponding attributes. These aircraft concepts include innovative solutions for propulsion systems, aircraft configurations, components integration, etc.

4.2.3 Morphological Matrices

After identifying attributes and their corresponding technological options, the MMs were derived based on the aircraft type. The derivation of MMs according to mission categorization is achieved by selecting an MM for the corresponding aircraft recommended as most suitable for the mission. For cargo applications, some attributes do not correspond to the passengers' applications. These are given and highlighted at the end of each matrix.

5 Results

5.1 UAM Vehicles Classifications and Applications

5.1.1 UAV Classes

UAV performance and technologies vary greatly depending on their size and weight, thus two common classifications were selected as a basis for identifying the abilities of different UAV types according to their weight class. The results of these findings are presented in the following table 5.1:

Weight Classes	Very Small $\leq$ 10kg	Small 10kg> $\leq$ 25kg	Medium 25kg> $\leq$ 150kg	Large 150kg> $\leq$ 600kg	Very Large >600kg
Regulations	EASA: Open Category FAA: sUAS		EASA Light UAS		EASA: small VTOL Aircraft Operations
Application types	Aerial Instruments	Freighter	Aerial Dispersers	Passenger	Emergency
UAV Configurations	Helicopters	Multirotors	Hybrids	Fixed-wing	

Table 5.1: Overall UAV categories

The first class in table 5.1 is for "Very Small" drones under $10kg$ take-off mass, which corresponds to group 1 in table 2.5. The next class is named "Small", which is the term given by the FAA for drones under $25kg$, and it corresponds to group 2 of table 2.5. UAVs under $150kg$ are considered in the "Medium" of the weight classes and they are part of Class I found in table 2.4. From the same table, Class II is represented as "Large" UAVs under $600kg$ take-off mass. Finally, the heaviest class is named "Very

Large" for drones above the $600kg$ corresponding to Group 5 and Class III in tables 2.4 and 2.5. Almost every class proposed in table 5.1 aligns with the weight classification given by the FAA and EASA. These are also included in the overall classification, however, for the very small and small UAVs the rules of operations for the Open Category (EASA 2023*b*) and sUAS (FAA 2022) do not apply due to the risk of UAM applications.

5.1.2 UAV Performance

The specifications of a total of 191 UAVs were collected, including 42 hybrids, 78 multirotors, 43 fixed-wings, and 29 helicopters. These are provided at the end of the document. Passengers carrying UAVs or air taxis were left off the list because complete information about their specifications is barely available. Nevertheless, future air taxis are easy to classify as very large UAVs with short endurances and heavy payloads. Emergency application types are not considered directly, since payloads used for these types of applications are the same as for aerial instruments (e.g., search and rescue), cargo (e.g., emergency delivery), and passenger UAVs (air ambulances). Thus, the majority of the aircraft can be suitable for emergency and fast-response missions. The overall space of the reference aircraft is shown in the following pictures (Grafica de Matlab con todos los drones). Two graphics are shown according to the payload classifications and the power source (Figures 5.1 and 5.2). The payload factor is chosen to allow a detailed visualization of the graphics.

Initially, certain trends of performance become evident. As anticipated based on the characteristics of multirotor aircraft discussed in Chapter 2.2.4, it is observed that multirotors possess the lowest airspeed and endurance among each UAV type. However, they are the most versatile aircraft type and can be used with every type of payload for short-endurance missions. A further noticeable characteristic relates to the superior capacity for endurance achievable with a fixed-wing aircraft. They are the most optimal option for long endurance and heavy payloads for cargo and instrument applications. Nevertheless, this trade-off involves the consideration of aircraft dimensions and the requirement for a suitable runway. When comparing fixed-wing

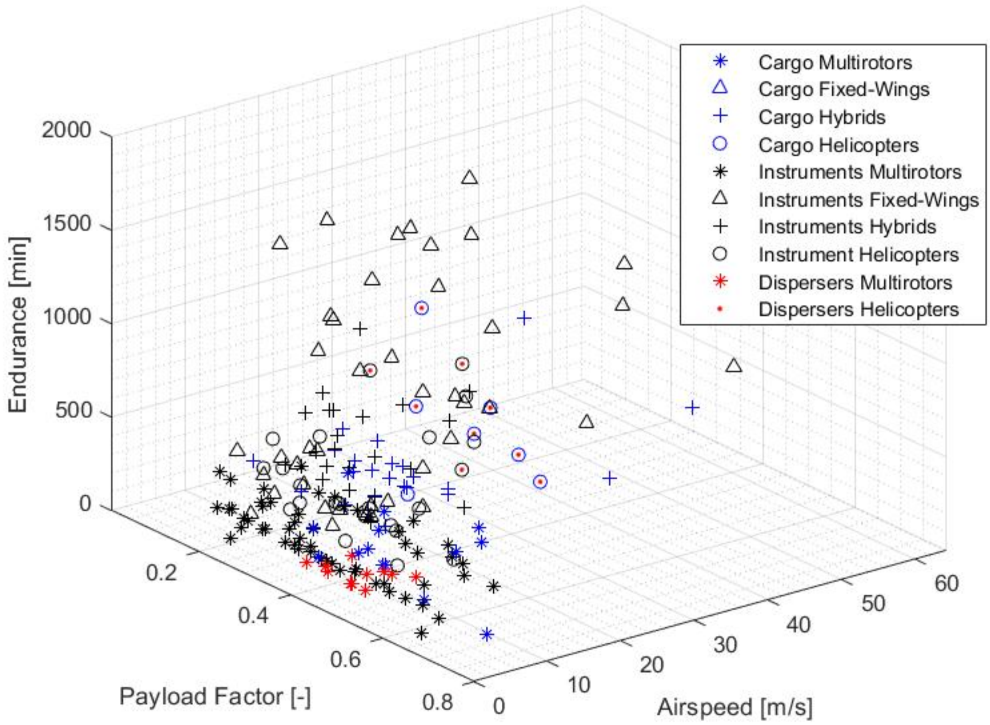

Figure 5.1: Overall Reference Drones by Application

aircraft to hybrid aircraft, it becomes evident that VTOL systems exhibit certain performance disadvantages. When considering the need for both VTOL capabilities and increased endurance and airspeed, hybrids are a more appropriate choice in contrast to multirotors. They are a more optimal option for cargo deliveries and medium to long endurance. The last aircraft type is the helicopter, which also shows the advantage of payload versatility found in the multirotor configuration However, they are able to reach significant endurance performance within the heavier weight classes. Additionally, there is a noticeable difference in endurance related to the various power sources. This topic will be further elaborated upon in the subsequent sections.

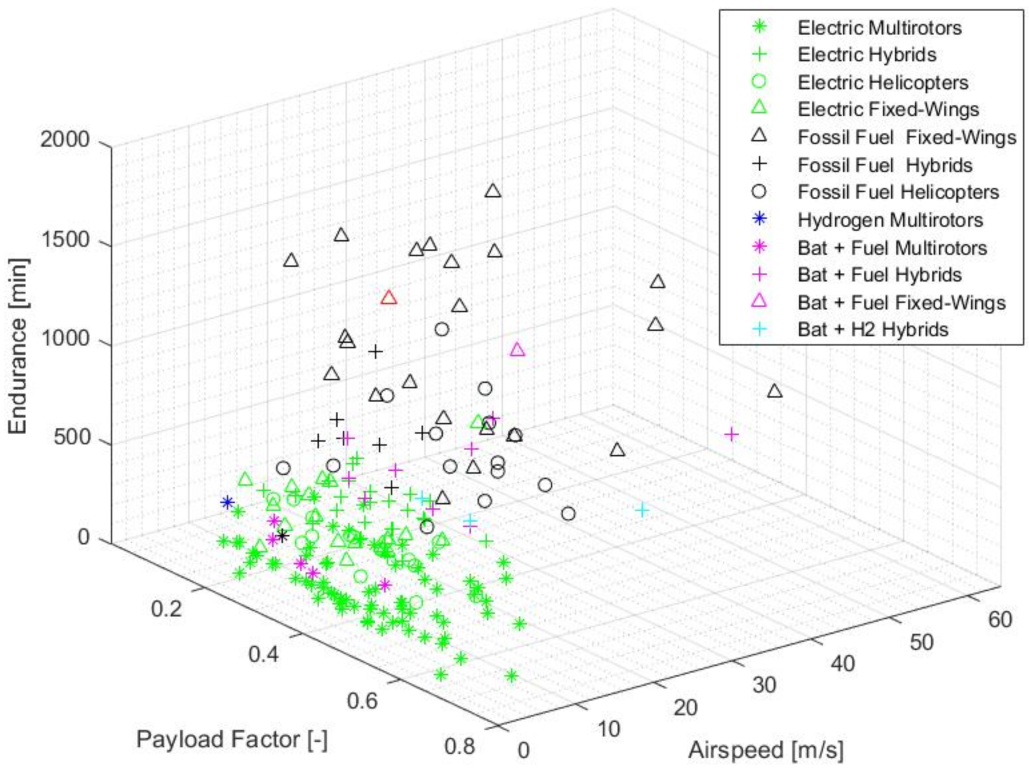

Figure 5.2: Overall Reference Drones by Fuel Type

Very Small and Small UAVs

It was found that very small (Table 5.2) UAVs under $10kg$ are able to carry payloads from 30% to 45% of their MTOM. In comparison to hybrids, multirotors have the advantage of being able to support an additional $1kg$ of payload. However, hybrids exhibit superior endurance capabilities, enabling them to sustain flight for extended durations. Fixed-wing have the greatest endurance, which is a trend that is noticeable in every weight class; however, they are only used for instrument applications. The highest payload of a fixed-wing also corresponds to the longest wingspan. Helicopters under the class of very small were not found. The utilization of batteries as an energy storage system is prevalent across all aircraft. The airspeeds of the types of aircraft are similar; however, an airspeed above $20m/s$ for a multirotor corresponds to the maximum flight speed.

Very Small UAVs				
Aircraft Type	**Max. Payload [kg]**	**Max.Endurance [min]**	**Airspeed [m/s]**	**Applications**
Multirotors	$1,5-3,5$	$30-65$ All Electric	$10-23$	Instrument Cargo
Fixed-Wing	$0,5-4,5$	$50-360$ All Electric	$12-20$	Instrument
Hybrids	$1-2$	$60-150$ All Electric	$16-30$	Instrument Cargo

Table 5.2: Performance of Very Small UAVs

For small UAVs (Talbe 5.3), every type of aircraft could be found. The increase in weight class results in an increase in the useful load and facilitates the integration of heavier engines. However, a significant majority of UAVs are battery-powered. They are able to transport payloads weighing up to $11kg$ depending on the dimensions of the aircraft. For cargo and instrument applications, short-duration missions lasting less than one hour can effectively employ hybrid aircraft, multirotors, and helicopters. Multirotors represent the only alternative for aerial dispersal. Battery-electric hybrid and fixed-wing aircraft have the capability to achieve endurance durations of up to four hours. However, if a different type of aircraft is utilized, it would necessitate the incorporation of hydrogen or fossil fuels as alternative power sources.

Medium, Large and Very Large UAVs

UAVs falling within the medium, large, and very large weight classes were less common. The prevalence of large and very large unmanned aerial vehicles (UAVs) in civilian applications is comparatively less widespread than their utilization in military applications. According to Table 5.4, medium unmanned aerial vehicles possess the capability to transport payloads exceeding $20kg$.Multirotors are the preferred choice for transporting heavier payloads, although at the expense of reduced flight endurance and range. They can deploy any type of payload, and enhanced endurance can be attained by employing hydrogen (H2) and fossil fuel (FF) energy sources. Helicopter UAVs

Small UAVs				
Aircraft Type	**Max. Payload $[kg]$**	**Max.Endurance $[min]$**	**Airspeed $[m/s]$**	**Applications**
Multirotors	$2,5-11$	BAT: $15-75$ FF: < 300 H2: $120-180$ BAT+FF: $175-240$	$7-20$	Instrument Cargo Disperser
Fixed-Wing	$0,5-11$	BAT: $110-450$ FF: $< 1200(20h)$ Solar: $1440(24h)$ BAT+FF: $< 1200(20h)$	$13-36$	Instrument
Hybrids	$2-10$	BAT: $20-240$ BAT+FF: < 300	$18-27$	Instrument Cargo
Helicopter	$5-10$	BAT: $30-120$	$12,5-25$	Cargo

Table 5.3: Performance of Small UAVs

can be considered a viable alternative for transporting payloads above $20kg$ in cases where a greater airspeed is deemed necessary. Hybrid and fixed-wing aircraft present a favorable alternative for the transportation of payloads within the weight range of $5kg$ to $30kg$ (and even slightly higher). These aircraft are particularly suitable for missions requiring endurance durations ranging from a minimum of 1.5 hours to a maximum of 6 hours.

Medium UAVs				
Aircraft Type	**Max. Payload $[kg]$**	**Max.Endurance $[min]$**	**Airspeed $[m/s]$**	**Applications**
Multirotors	$10-70$	BAT: $15-70$ FF: < 240 H2: $120-180$	$7-25$	Instrument Cargo Disperser
Fixed-Wing	$4-35$	BAT: $180-480$ FF: $360-1440(24h)$	$22-45$	Instrument Cargo
Hybrids	$5-25$	BAT: $120-300$ FF: $360-840$ BAT+FF: $360-840$ H2: 330	$20-40$	Instrument Cargo
Helicopter	$7-40$	BAT: < 75 FF: < 350	$12,5-55$	Intrument Cargo

Table 5.4: Performance of Medium UAVs

Large UAVs				
Aircraft Type	**Max. Payload [kg]**	**Max.Endurance [min]**	**Airspeed [m/s]**	**Applications**
Multirotors	$100-200$	BAT: $21-30$ H2: <180	$8-27$	Cargo
Fixed-Wing	$30-250$	FF: $720-1200(20h)$	$27-57$	Instrument Cargo
Hybrids	<150	BAT+FF: <150	$40-65$	Cargo
Helicopter	$90-180$	BAT: <90 FF: $120-420$	$22-39$	Instrument Cargo

Table 5.5: Performance of Large UAVs

The maximum performance data of large and very large UAVs is shown in Tables 5.5 and 5.5. Limited data is available regarding reference vehicles for large and very large multirotors and hybrids, making it challenging to draw definitive conclusions about their performance. However, some of the reference aircraft found are used as cargo UAVs. The reference aircraft for hybrid and multirotor are innovative concepts expected to be utilized in UAM as cargo drones (VoloDrone, Ehang 216L, Moya). These concepts integrate batteries as energy sources and DEP. Although they can carry a similar payload weight, the hybrid UAV can reach a range of $110km$ in comparison to ranges under $25km$ of both multirotors. The predominant UAV types for large and very large classes are helicopters and fixed-wing aircraft. Fixed-wing aircraft possess the highest levels of endurance and payload capacity. Nevertheless, the operation of these aircraft necessitates the presence of a runway for both takeoff and landing procedures. Helicopters powered with fossil fuels are a viable option for achieving moderate endurance.

5.1.3 Cargo Missions

After presenting the performance specifications for every type of aircraft depending on their weight classes, a detailed discussion of cargo drones is followed to address the case of UAM applications. For this, only endurance with a duration of less than four hours is included for analysis. Cargo deliveries within an urban or suburban environment are typically characterized by short flight durations. As an example, the fastest deliveries

Very Large UAVs				
Aircraft Type	**Max. Payload** [kg]	**Max.Endurance** [min]	**Airspeed** [m/s]	**Applications**
Multirotors	< 200	BAT: $21 - 30$	< 23	Cargo
Fixed-Wing	$55 - 250$	FF: $1200 - 1620(27h)$	< 40	Instrument Cargo
Hybrids	< 460	BAT: 42 H2: < 720	$40 - 50$	Cargo
Helicopter	$90 - 180$	FF: 360	$22 - 39$	Instrument Cargo

Table 5.6: Performance of Very Large UAVs

for the company Wing was achieved under 3 minutes (Wing 2023). An aircraft will not be required to fly continuously for a long period of hours. Therefore, endurance over 4 hours are not taking into consideration in the case of cargo transportation. Nevertheless, reducing charging and refueling times can improve operational factors, leading to increased efficiency and productivity (Uber 2022). The aircraft could be sized for longer endurance, in order to accommodate various VTOL procedures for fast deployment after one mission was completed. An aircraft-type recommendation is provided for each performance metric, taking into account the findings from the preceding sections of this chapter. In order to align with the expectation of electric-powered UAM aircraft, only battery-powered vehicles are recommended for most scenarios, except in instances where the payload exceeds $200kg$ or when the desired endurance is longer than 4 hours. These findings are presented in Table 5.7.

Multirotors are suggested for flight durations of less than 30 minutes due to their limited endurance capabilities. Nevertheless, they can serve as a feasible alternative for transporting the largest payloads within each respective weight class. While it may not be the most efficient method for transporting objects between locations, utilizing multirotors at lower airspeeds offers increased stability and enhanced safety for maneuvering within the confined airspace of urban environments. In situations where an extended range is necessary, helicopters may present an advantageous choice for the transportation of large payloads. Nevertheless, the utilization of helicopters could increase the potential hazards of the flight mission when compared to multirotor aircraft.

Cargo UAVs						
Class	**Very Small/Small**		**Medium**		**Large/Very Large**	
	Performance	**Aircraft Type**	**Performance**	**Aircraft Type**	**Performance**	**Aircraft Type**
Endurance	$< 30min$	(BAT) Multirotor	$< 30min$	(BAT) Multirotor	$< 30min$	(BAT) Multirotor
	$< 60min$	(BAT) Multirotor/ Hybrid/ Helicopter	$< 60min$	(BAT) Multirotor/ Helicopter	$< 60min$	(BAT) Hybrid
	$< 240min$	(BAT) Hybrid	$< 240min$	(BAT) Hybrids	$< 240min$	(BAT+FF /H2) Hybrids
Payloads	$< 2kg$	Hybrid	$< 10kg$	Hybrids	$< 50kg$	Hybrids
	$< 5kg$	Multirotor/ Hybrid/ Helicopter	$< 20kg$	Multirotor/ Hybrid/ Helicopters	$< 200kg$	Multirotors
	$< 10kg$	Multirotor/ Helicopter	$< 50kg$	Multirotor/ Helicopters	$> 200kg$	Hybrids
Airspeeds	$< 15m/s$	Multirotor	$< 15m/s$	Multirotors	$< 30m/s$	Multirotors
	$< 20m/s$	Helicopter	$< 20m/s$	Helicopters	$< 50m/s$	Helicopter
	$> 20m/s$	Hybrids	$> 20m/s$	Hybrids	$> 50m/s$	Hybrids

Table 5.7: Performance of selected Cargo Drones for UAM missions

The consideration of fixed-wing aircraft is acknowledged; nevertheless, their requirement for a launch mechanism makes them less suitable to take off and land within urban environments. Additionally, fixed-wing cannot hover over the destination and they are required to throw the cargo while flying horizontally. However, these vehicles have the potential to facilitate the transportation of large cargo between hubs situated in airports of the same city. Hybrid vehicles are considered the most optimal choice for transporting lower payloads within a specific weight class, particularly when the primary requirements involve range and higher airspeeds.

The UAM missions for cargo UAVs are presented in Table 5.8. Last-mile and middle-mile delivery are the two use cases chosen. A last-mile delivery begins at the hub and ends at the buyer's final destination address (Hasan 2018). Middle-mile deliveries take place between the hubs of various retailers within the same city. This may include additional transportation from airports or major ports to the retailer's hub. Missions are assigned for both use cases based on the payload masses specified in Table 5.7.

Cargo Transport				
Use Case	**Mission**	**Payload** $[kg]$	**Range** $[km]$	**UAV Class**
Last Mile Delivery / Emergency Deliveries	Small Payload	< 2	< 25	Very Small
	Medium Payload	< 5		Small
	Heavy Payload	< 10		Small/ Medium
Middle Mile Delivery	Small Payload	< 50	> 25 < 70	Medium
	Medium Payload	< 200		Large
	Heavy Payload	> 200		Very Large

Table 5.8: Cargo Missions

The determination of the minimum weight class necessary to accommodate the desired payload is made, thereby facilitating the identification of an appropriate aircraft model. In order to accommodate the designer's personal preference, no particular aircraft type has been specified. Furthermore, the ranges from Table 2.1 are chosen. TLARs for cargo applications can be further selected according to the outlined missions.

The payload has the potential to be deployed during the aircraft's stationary position above the intended location through the utilization of a lowering mechanism, such as a hook or another comparable apparatus. Nevertheless, it is not advisable to employ this method for payloads exceeding a mass of $5kg$ due to the possible increase of the dropping mechanism's weight to handle the loads of the delivery procedure. Consequently, in the case of payloads exceeding 10 kg, it becomes essential for the aircraft to land in order to release the payload.

5.1.4 Passenger Mission

To classify passenger air vehicles, the literature was used to identify similarities among various UAM missions (see Chapter 2.1.2, Table 2.3). These results are presented in

<table>
<tr><th colspan="9">Passenger Transport</th></tr>
<tr><th>Use Case</th><th>Mission</th><th>Payload $[PAX, kg/PAX]$</th><th>Total Range $[km]$</th><th>Single Range $[km]$</th><th>VTOLs $[-]$</th><th>Hover Time $[min]$</th><th>Airspeed $[m/s]$</th><th>Aircraft Type</th></tr>
<tr><td>Intra-City (scheduled)</td><td rowspan="2">Short Range</td><td>2-4, 90-100</td><td rowspan="2">< 50</td><td rowspan="2">< 17</td><td>3</td><td>6-8</td><td>Low</td><td>Multirotor</td></tr>
<tr><td>Intra-City (on-demand)</td><td>1-2, 90</td><td>3</td><td>6-8</td><td>Low</td><td>Multirotor</td></tr>
<tr><td>Metropolitan (scheduled)</td><td rowspan="2">Medium Range</td><td>$4-6$, 90-100</td><td rowspan="2">70 - 100</td><td rowspan="2">35 - 50</td><td>2</td><td>4-6</td><td>Medium</td><td>Lift + Lift/Cruise</td></tr>
<tr><td>Metropolitan (on-demand)</td><td>1-4, 90</td><td>2</td><td>4-6</td><td>Medium</td><td>Lift + Cruise</td></tr>
<tr><td>Megacities (scheduled)</td><td rowspan="2">Long Range</td><td>4-6, 90-100</td><td rowspan="2">< 140</td><td rowspan="2">< 70</td><td>2</td><td>4-6</td><td>Fast</td><td>Lift + Lift/Cruise</td></tr>
<tr><td>Megacities (on-demand)</td><td>1-4, 90-100</td><td>2</td><td>4-6</td><td>Fast</td><td>Tilt-Rotor</td></tr>
<tr><td>Airport Shuttle Services (both)</td><td rowspan="2">Short Range</td><td rowspan="2">$4-6$, 110</td><td rowspan="2">30 - 70</td><td rowspan="2">15-35</td><td rowspan="2">2</td><td rowspan="2">4-6</td><td rowspan="2">Medium</td><td rowspan="2">Lift + Cruise or Lift + Lift/Cruise</td></tr>
<tr><td>Air Ambulance</td></tr>
</table>

Table 5.9: Passenger Carrying Missions

Table 5.9. The TLARs are derived from the literature researched in Chapter 2.1.2. The combined flight range and VTOL requirements, then the payload, determine the recommended and chosen aircraft type. The airspeed of an aircraft is qualitatively estimated based on two primary factors, namely flight range and VTOL capabilities. In essence, aircraft with a greater frequency of take-offs and landings, as well as shorter range capabilities, necessitate increased flight maneuverability for operational safety in dense urban environments. Consequently, a lower airspeed is recommended in such scenarios.

Intra-city and airport shuttle missions are examples of the short-range sector for UAM. The latter use case, however, requires a heavier payload capacity in order to accommodate a larger number of passengers and their corresponding luggage. For intra-city missions, multirotor aircraft are chosen due to the number of VTOLs and low airspeed requirements. The number of passengers also plays a role in this selection. UAM multirotor concepts such as the VoloCity (Volocopter 2021) and Ehang (Ehang 2023) accommodate only 2 passengers. Therefore, a multirotor in a 4-passenger configuration is a very constrained requirement. Furthermore, hybrid configurations with independent and combined lift and thrust units (lift plus cruise and lift plus lift/cruise) are chosen due to the higher number of passengers. Aircraft concepts that can fulfill the airport shuttle TLARs are the Midnight (eVTOl News 2023*a*), the Wisk Aero Gen 6 (Aero 2023), the VoloRegio (VoloCopter 2023), and the Eve eVTOL (Eve 2023). These hybrids are configured in the selected configuration.

Medium-range missions are assigned to the metropolitan use case. Due to a greater flight range, the cruise airspeed increases in comparison to short-range missions. The aircraft type chosen resembles the same concepts as for the airport shuttle mission because of the similarities in TLARs. However, for the scheduled service, the combined LTU hybrids are preferred due to their higher payload capabilities (see cited aircraft concepts). The on-demand mission could represent the air pooling case proposed by Uber (2016), where hybrids with independent LTUs are preferred.

The wider urban areas of megacities make this use case a long-range mission. Once again, the decision has been made to opt for a hybrid aircraft. However, for the on-demand case with 1 to 4 passengers, an aircraft such as the Joby S4 (eVTOL News 2023*b*) using the same LTU for both flight conditions can fulfill the long-range mission without leaving passenger seats empty. The scheduled missions will require a heavier payload, and the combined LTU configuration is chosen.

For UAM passenger transport, other aircraft types were ruled out. Fixed-wing aircraft are not considered because they require a runaway. Due to the infrastructure requirements (Chapter 2.1.4), they would only be suitable in cities with two or more airports. Helicopters could be an option; however, they are ruled out because of their noise characteristics due to their large rotor and safety factors (Uber 2022; Cohen et al. 2021).

5.2 Morphological Analysis of UAM aircraft

A major aim of this work was to structure and systematize morphological matrices for the design of unmanned UAM aircraft. The results of the attributes and technological identification for the derived MMs are presented in this section of the thesis.

5.2.1 System's Attributes

Following the theoretical background of the morphological analysis, a system decomposition of each type of aircraft into its main functionalities was carried out. In this study, the aircraft were initially classified based on their method of lift generation. Consequently, two distinct categories emerged, namely fixed-wing and rotary-wing classes. Each of these classes was further divided into distinct categories, namely fixed-wing aircraft, hybrid aircraft, helicopters, and multirotor aircraft. As explained in Chapter 2.2.4, the various air vehicle types exhibit distinct functionalities in their operation as aerial vehicles. Therefore, MMs were derived for each type of aircraft. However, it was decided to build one MM for the multirotor and helicopter types due to similarities in their functionalities. The MM are presented in the appendix A.1.

It must be mentioned that attributes that take into consideration the autopilot system were left out. Vehicle autonomy is an important technological requirement that is required for efficient operations for UAM Uber (2022). However, different sensors must be included in the airframe to allow vehicle autonomy were not considered as the main system to take into account during the conceptual design stage.

Hybirds Attributes

The most complex system is the hybrid aircraft. This was expected, as they combined both multirotor and fixed-wing functionalities. Additionally, the complex mechanism used to transition allows for different flight control methods to be used (such as thrusting the vector and tilting the propellers). The hybrid airframe shares common attributes with fixed-wing aircraft and therefore offers similar technological and integration options. Nevertheless, they were not included in the same MM, since fixed-wing aircraft are not the best option for UAM applications. As a first attribute, the type of lift and thrust unit (independent, equal, or combined) with the transition mechanism was preferred. This attribute defines the aircraft configuration. The type of propulsor for vertical and horizontal flight was divided into two different attributes, namely the vertical propulsor type and the horizontal propulsor type.

Additional complexity is added when considering the design freedom that distributed electric propulsion brings to the system. With the implementation of DEP, the propulsor can be integrated on top, under, front, aft, and inside almost every component of the airframe. Therefore, the integration into a certain component was separated into different system attributes (on the wing, on the fuselage, etc.). However, to consider the direction of the propulsor, namely on the front or aft of the component, an attribute to consider aero-propulsive integration possibilities was derived. The propulsion system was first divided into its main components. However, to reduce the generation of non-feasible solutions, an attribute considering energy storage and the powertrain architecture was derived. Further functionalities with their corresponding attribute are outlined in the MMA.1.

The integration of the payload is also considered as an attribute. Additionally, for cargo applications attributes are derived describing the method of delivery and the number of payloads integrated in the system.

Rotorcraft Attributes

the rotorcraft systems exhibited the least complexity in terms of attribute decomposition. Chapter 2.2.4 explained the way in which the lift generation method and the torque balanced method can be collectively designated as a fundamental attribute. Nevertheless, an abundant number of technological options were identified for that particular attribute, and conducting, and a further criteria evaluation would have been too complicated. Consequently, three distinct attributes were derived, specifically the number of rotors, the alignment of the rotors, and the torque balance systems. Rotorcraft have the capability to incorporate additional systems that assist in the production of lift and thrust while performing cruise flights. These attributes were considered separate, and additional attributes were derived based on the component's type and integration. Each functionality is presented alongside its respective attributes A.2.

Fixed-wing

While fixed-wing aircraft may not be the most optimal choice for the mission requirements explored in the context of UAM, it is still possible to create a morphological matrix as the attributes of this aircraft type share similarities with hybrid aircraft. The hybrid's MM takes into account the majority of fixed-wing attributes for the arrangement of aerodynamic surfaces, the type of the wing, the configuration of the empennage, the position of the propulsors, and further. Every functionality is listed next to its corresponding attribute in MM for fixed-wingsA.3. The first attribute to consider is the configuration of lift and trim surfaces. The methods employed for take-off, launch, landing, and recovery are distinct characteristics that are unique to these particular types of aerial vehicles. Furthermore, Aero-propulsive integrations are recognized as a characteristic of fixed-wing aircraft as well.

5.2.2 Technological Options

Chapter 2.1.3 of the literature review highlights the most relevant technologies which develop the concepts of UAM applications. The literature on UAV design revealed traditional technologies and integration possibilities considered for concept design (Gundlach 2014; Fahlstrom and Gleason 2012; Sadraey 2020). The reference aircraft obtained in this study contribute to the identification of additional technological possibilities, including payload deployment systems, modular airframes, and closed-wing bodies (Jetoptera 2023; Fixar 2023*b*).A selection of innovative aircraft concepts, including the Lilium jet, Helix, Joby S4, VoloDrone, VoloRegio, Midnight Archer, Wisk Aero, Eve eVTOL, AirbusCity, Ehang 216, and Jetoptera, were utilized as reference models to facilitate a comprehensive examination of technologies and the integration of components for prospective air taxi aircraft (Lilium 2023; Pivotal 2023; eVTOL News 2023*b*; Electric VTOL news 2023*b*; VoloCopter 2023; Ehang 2023; Ascendance 2023; Airbus 2023; Aero 2023; eVTOl News 2023*a*). The results are shown in the respective Morphological Matrices in the appendix A.1.

6 Conclusion

The Chair of Aircraft Design and Aerostructures at Technische Universität Berlin is proposing a novel conceptual design method for innovative aircraft concepts. The objective of the Advanced Morphological Approach is to assist designers in enhancing their creativity and tackling the significant challenges of uncertainty that arise in the initial phases of the design process. The utilization of unmanned Urban Air Mobility Vehicles has been suggested as a subject for further investigation according to this novel design methodology.

The starting point of the project involved conducting a literature review on the Advanced Morphological Approach and the underlying principles of unmanned Urban Air Mobility (UAM) aerial vehicles. The present task was successfully resolved and subsequently presented as the state-of-the-art and theoretical background of this study. Chapter 2.1 explored the description of the UAM concept, encompassing its missions, aircraft technologies, and technical requirements. Passenger, cargo and emergency services for UAM were identified. Additional research was conducted on the subject of Unmanned Aerial Vehicles (UAVs) as the appropriate aircraft to be employed in this mode of transportation. Chapter 2.2 provided a comprehensive overview of UAV classes, applications, and various types of aircraft. This study selected four distinct categories of aircraft for further examination: fixed-wing, hybrid, multirotor, and helicopters. The components and primary functionalities of the system were discussed in Chapter 2.2.4. Furthermore, the theoretical framework related to the Conceptual Design Phase and the Advanced Morphological Approach has been explained in Chapters 3.1 3.2. The utilization of Morphological Analysis as a method for addressing the challenges associated with the structural synthesis of complex structures was explained in Chapter 3.2.2.

The task of classifying vehicle missions was addressed in chapter 5.1. The classification of appropriate aerial vehicles based on their mission requirements is presented in Tables 5.8 and 5.9. This process began Starting from global UAVs applications to the chosen UAM use cases, suitable air vehicles were classified according to their mission requirements in the Tables 5.8 and 5.9. In order to analyze the performance trends of various aircraft types, a detailed list of reference unmanned aerial vehicles (UAVs) along with their respective performance specifications was generated and employed. The aforementioned methodology was also employed in the context of future urban air mobility (UAM) air taxis. However, the absence of specific data the list was not created for air taxis. Nevertheless, the UAVs reference vehicles and relevant air taxi concepts were employed to identify additional aircraft attributes, technological possibilities, and system integration. The generation of the Morphological Matrix was subsequently carried out for fixed-wing aircraft, hybrid aircraft, and rotorcraft. The attributes were obtained through a comprehensive review of the existing literature and are outlined in Chapter 5.2. The overall matrices are presented in the appendix A.1.

A methodology proposed for quantitative evaluation was introduced in Chapter 3.3 based on the Max-Min Normalization Method. This will allow the derivation of a relative unitless scale. However, due to limitations, a quantitative assessment of the technological options could not be carried out. Furthermore, a method to perform a qualitative comparison between technologies could not be developed within the timeframe of the work.

6.1 Limitations

The nature and the context of this work proposed several limitations to this work.

- The existing UAV classifications from the literature were considered inappropriate for categorizing air vehicles according to UAM missions because the concept of UAM exhibits different TLARs than the common UAV missions.

- The novelty of this transportation method is a significant limitation in many aspects, including the uncertainty of operation concepts and missions, which has led many authors of the presented literature to assume different TLARs.
- Collecting aircraft performance metrics was a long and not clear process due to the lack and mixed specifications provided by the manufactures
- Although the most common aircraft types were chosen for further study, other unconventional UAVs such as Gyrocopters and flapping wing could be studied to determine if they are suitable for UAM applications
- The complexity of the hybrid aircraft resulted in an extended list of attributes. This represents a challenge to further stages of the AMA
- There is a lack of quantitative experimental data to perform technology assessment for unmanned UAM vehicles.
- The complexity of conducting a technology assessment for each option within an attribute is further complicated by the limited inclusion of only two or three technologies in experimental studies.

6.2 Future Work

Given that the evaluation of criteria was not conducted, it is essential for this task to be prioritized as the initial step in forthcoming research efforts. Once the target has been reached, the subsequent phases of the Advanced Morphological Approach can be executed.

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Appendix

A.1 Morphological Matrices

Hybrids								
Functions	P_x	**Attributes**	**Option** P_x^1	**Option** P_x^2	**Option** P_x^3	**Option** P_x^4	**Option** P_x^5	**Option** P_x^6
Thrust generation in flight direction Flight transition	1	**Lift +** **Thrust +** **Transition**	Independent thrust systems (Lift + Cruise)	Same thrust systems (Lift = thrust) With tilting rotors	Same thrust systems (Lift = thrust) With tilting wing	Same thrust systems (Lift = thrust) With tilting body	Combined Propulsion Systems (Lift + Lift/Cruise) With some tilting rotors	Combined Propulsion Systems (Lift + Lift/Cruise) With a horizontal surface tilting
Energy source and storage Propulsion system architecture	2	**Energy** **Storage +** **Powertrain**	Battery Fully Electric	Battery + Fuel Tank Serial hybrid	Battery + Fuel Tank Parallel Hybrid	Fuel Tank	Hydrogen + Fuel cell Fully Electric	Battery + Hydrogen and Fuel Cell Hybrid Electric

External Energy Supply	3	**External Energy Supply**	Non	Solar	Laser	Tank		
Power generation	4	**Engines**	Electric Motors	Internal Combustion Engine	Gas Turbine			
Power distribution from power source to propulsor	5	**Power Distribution**	Central	Distribute				
Gearbox	6	**Gearbox**	Non	Yes				
Horizontal Propulsor	7	**Horizontal Propulsor**	Open Propeller	Fan Propeller	Bladeless	Arc Reaction Engine		

Vertical Propulsor	8	**Vertical Propulsor**	Non	Open Propeller	Ducted Propeller	Open Co-axial Propeller	Ducted Co-axial Propeller	
Propulsion and cruise efficiency	9	**Propulsion adaptation**	Non	Variable Propeller Speed	Variable Pitch Propeller	Variable Exhaust Area	Variable Intake Area	Blade Retraction
			Option P_x^7	-				
			Rotor retraction in the airframe					

Moment generation for vertical flight stability and manoeuvring	10	**Stability and Moment (y-axis)**	Symmetrical Propeller Tilting	Variable Speed Propeller	Cyclic Pitch Propellers	Collective Aileron deflection under propeller wake	Mass distribution control (front/aft)	
	11	**Stability and Moment (x-axis)**	Symmetrical Propeller Tilting	Variable Speed Propeller	Cyclic Pitch Propellers	Differential Aileron deflection under propeller wake	Mass distribution control (front/aft)	
	12	**Stability and Moment (z-axis)**	Asymmetrical Propeller Tilting	Variable speed propellers	Rudder Deflection			

Moment generation for horizontal flight stability and manoeuvring	13	**Flight Control**	Aerodynamic Surfaces	Symmetric/ Asymmetric Thrust generation	Vectored Thrust			
	14	**Aero-Propulsive**	Non	High-Lift Propeller	Boundary Layer Ingestion	Induced Drag Reduction	High-Lift Propeller + Induced Drag Reduction	Boundary Layer Ingestion + Induced Drag Reduction
	15	**On Wing**	Non	Twin Propulsors	Distributed Propulsors on airframe	In the Airframe		
	16	**On Empennage**	Non	Yes				

Propeller / Rotor Integration	17	**On Fuselage**	Non	Twin Propulsors	In the Airframe			
	18	**On Booms**	Non	Yes				
Fuselage integration	19	**Fuselage**	Fixed	Detachable				
Lift generation / Longitudinal Stability	20	**Lift + Trim**	Wing + horizontal stabilizer	Canard + Wing	Canard + Wing + horizontal stabilizer	Tandem wings	Joined Surfaces	Single surface
Fuselage	21	**Fuselage**	Single	Twin	Blended Wing Body			
Empennage attachment	22	**Tail integration**	Fuselage	Tail Booms	Both			

Tail Configuration	23	**Tail**	Conventional	T-Tail	Cruciform	H-Tail	V-Tail	Inverted V
			Option P_x^7					
			X-Tail					
Wingtips	24	**Wingtips**	Non	Upwards	Downwards			
Lift Augmentation	24	**High Lift Devices**	Non	Flaps	Slats	Both		
On Ground Support	25	**Landing Support**	Landing Gear	Landing Skids	Airframe			
	26	**Landing Support**	Fixed	Retractable				
For cargo applications								
Payload Delivery	27	**Payload Deployment**	On Ground	Hovering (hook)	Airborne (Thrown)			

Number of payloads	28	**Payload**	Single	Multiple				
Payload Accommodation	29	**Payload Location**	Fuselage	Wing	Both			

Rotorcrafts

Functions	P_x	**Attributes**	**Option** P_x^1	**Option** P_x^2	**Option** P_x^3	**Option** P_x^4	**Option** P_x^5	**Option** P_x^6
Lift and Thrust Production	1	**Number of Rotors**	1	2	Multiple			
Rotor Alignment	2	**Rotor alignment**	Isolated	Overlapped	Coaxial			
Torque balance system	3	**Torque balance**	None	Tail-rotor	Fan	Circulation (e.g NOTAR)		
Rotor attachment to the hub	4	**Rotor hub**	Articulated	Teetering	Hingeless	Bearingless		
Rotor type	5	**Rotor**	Open	Ducted				

Addition lift generation surface	6	**Lift augmentation**	None	Wing	Half	Wing		
	7	**Wing Type**	None	Single Wing	Box-wing	Bi-wing		
Longitudinal Stability	8	**Horizontal Stabilizer**	None	Front	Aft	T-tail		
Lateral Stability	9	**Vertical Stabilizer**	Vertical Fin	Twin				
Addition forward thrust system	10	**Forward thrust augmentation**	None	Single	Twin	Distributed		
	11	**Propulsor Position**	None	Pusher	Puller			
	12	**Propulsor type**	None	Open Propeller	Ducted			

Energy source and storage Propulsion system architecture	13	**Energy Storage + Powertrain**	Battery Fully Electric	Battery + Fuel tank Serial hybrid	Battery + Fuel Tank Parallel Hybrid	Fuel Tank	Hydrogen + Fuel cell Fully Electric	Battery + Hydrogen and Fuel Cell Hybrid Electric
External Energy Supply	14	**External Energy Supply**	Non	Solar	Laser	Tank		
Power generation	15	**Engines**	Electric Motors	Internal Combustion Engine	Gas Turbine			
Power distribution from power source to propulsor	16	**Power Distribution**	Central	Distribute				

Gearbox	17	**Gearbox**	Non	Yes				
Flight Control and Maneuvering	18	**Lateral / Longitudinal Control**	Cyclic	Differential Collective	Rotor Speed Control			
	19	**Height Control**	Collective	Rotor Speed Control				
	20	**Directional Control**	Torque Balance System	Torque Disbalance				

Fixed-wings								
Functions		**Attributes**	**Option P_x^1**	**Option P_x^2**	**Option P_x^3**	**Option P_x^4**	**Option P_x^5**	**Option P_x^6**
Lift generation Longitudinal Stability	1	**Lift + Trim**	Wing + horizontal stabilizer	Canard + Wing	Canard + Wing + horizontal stabilizer	Tandem wings	Joined Surfaces	Single surface
Fuselage	2	**Fuselage**	Single	Twin	Blended Wing Body			
Empennage attachment	3	**Tail integration**	Fuselage	Tail Booms	Both			
Tail Configuration	4	**Tail**	Conventional	T-Tail	Cruciform	H-Tail	V-Tail	Inverted V
			Option P_x^7					
			X-Tail					
Wingtips	5	**Wingtips**	Non	Upwards	Downwards			

Lift Augmentation	6	**High Lift Devices**	Non	Flaps	Slats	Both		
Take-off and launched method	7	**Take off/ Launch**	Runaway	Hand Launched	Catapult Launched	Bungee Lauch		
Landing and recovery method	8	**Landing/ Recovery**	Runaway	Belly Landing	Parachute	Hook	Net Catching	
Landing gear retraction	9	**Landing Gear**	Non	Fixed	Retractable			
Assembly for transportation	10	**Assembly**	Fixed airframe	Modular Airframe				

Number of payloads	11	**Payload**	Single	Multiple				
Payload Accommodation	12	**Payload Location**	Fuselage	Wing	Both			
Moment generation for stability and manoeuvring	13	**Flight Control**	Aerodynamic Surfaces	Thrust Imbalance	Vectored Thrust			
	14	**Aero-Propulsive**	Non	High-Lift Propeller	Boundary Layer Ingestion	Induced Drag Reduction	High-Lift Propeller + Induced Drag Reduction	Boundary Layer Ingestion + Induced Drag Reduction
	15	**On Wing**	Non	Twin Propulsors	Distributed Propulsors on airframe	In the Airframe		

Propeller / Rotor Integration	16	**On Empennage**	Non	Yes				
	17	**On Fuselage**	Non	Twin Propulsors	In the Airframe			
Energy source and storage Propulsion system architecture	18	**Energy Storage + Powertrain**	Battery Fully Electric	Battery + Fuel tank Serial hybrid	Battery + Fuel Tank Parallel Hybrid	Fuel Tank	Hydrogen + Fuel cell Fully Electric	Battery + Hydrogen and Fuel Cell Hybrid Electric
External Energy Supply	19	**External Energy Supply**	Non	Solar	Laser	Tank		
Power generation	20	**Engines**	Electric Motors	Internal Combustion Engine	Gas Turbine			

Power distribution from power source to propulsor	21	**Power Distribution**	Central	Distribute				
Gearbox	22	**Gearbox**	Non	Yes				
Horizontal Propulsor	23	**Propulsor**	Open Propeller	Fan Propeller	Bladeless	Arc Reaction Engine		

A.2 List of reference UAVs