# Urban Air Mobility Vehicle- and Fleet-level Life-Cycle Assessment Using a System of Systems Approach

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**Can Urban Air Mobility (UAM) systems constitute viable and sustainable mobility solutions? This question has increasingly been concerning scientists, companies, policy makers, and authorities as more and more UAM vehicle concepts are seeing the light of day. In order to come closer to answering this question and to demonstrate the dependencies and impacts of the numerous parameters used to describe a highly complex system of a fleet of UAM vehicles operating in an urban environment, this paper employs a System of Systems (SoS) approach. A collaborative SoS framework with an agent-based simulation is introduced, which connects the UAM vehicle design, fleet performance, vertiport network, and re-energizing infrastructure with a Life-Cycle Assessment (LCA). The framework is used to simulate four exemplary UAM fleet-operation scenarios based on two cities and two operational modes, namely urban and suburban operations. Different vehicle design configurations, e.g. multirotor and lift + cruise vehicles, are evaluated in each scenario based on respectively realistic Concepts of Operations (CONOPS). Additionally, two different points in time, namely 2025 and 2050, are considered and assessed for powering the vehicles by taking into account the characteristics of batteries as well as the underlying electricity mix for their operation. Lithium nickel manganese cobalt oxide battery and lithium-sulfur (Li-S) batteries are considered. The SoS framework helps to asses various UAM metrics such as the average wait time for a passenger, the ideal number of aircraft needed for transporting all passengers within given time, the energy required on a vehicle and fleet level, sustainability metrics, e.g. the global warming potential associated with the energy carriers and many more. The capability to explore a wide design space and to visualize the dependencies between the system parameters and their impacts on different SoS metrics provides stakeholders with a helpful tool for their decision making.**

## I. Introduction

System of Systems (SoS) has been recently formalized by ISO 21839:2019 [1] as a set of systems that interact and provide unique capabilities that the individual constituent systems cannot accomplish on their own. SoS is an emergent concept that is widely accepted as a tool to understand complex systems in fields such as renewable energy, national security, infrastructure, transport and defense [2]. Although each field has adopted a specialized definition of SoS to suit their needs, the influential work of Maier [3] has provided a widely accepted characterization of SoS [4]. These are referred to as the Maier criteria or OMGEE characteristics [5] and are namely: Operational & Managerial Independence, Geographic Distribution, Emergence, and Evolutionary Behavior.

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Urban Air Mobility, as shown in Fig. 1, has constituent systems such as the vehicle, the heterogeneous fleet, the vertiport system, air-traffic operations (trajectory, conflict resolution, safety), the passenger demand, the energy system and its life-cycle aspects at vehicle, fleet and grid levels. These systems are operationally and managerially independent. The constituent systems put together make a SoS, which needs to collaborate for successful efficient operation or to achieve positive emergence.

Moreover, each of the constituent systems is geographically distributed and evolves independently at individual points in time (e.g. new vehicles are introduced, new energy, smart grid, new ATM procedures etc.).

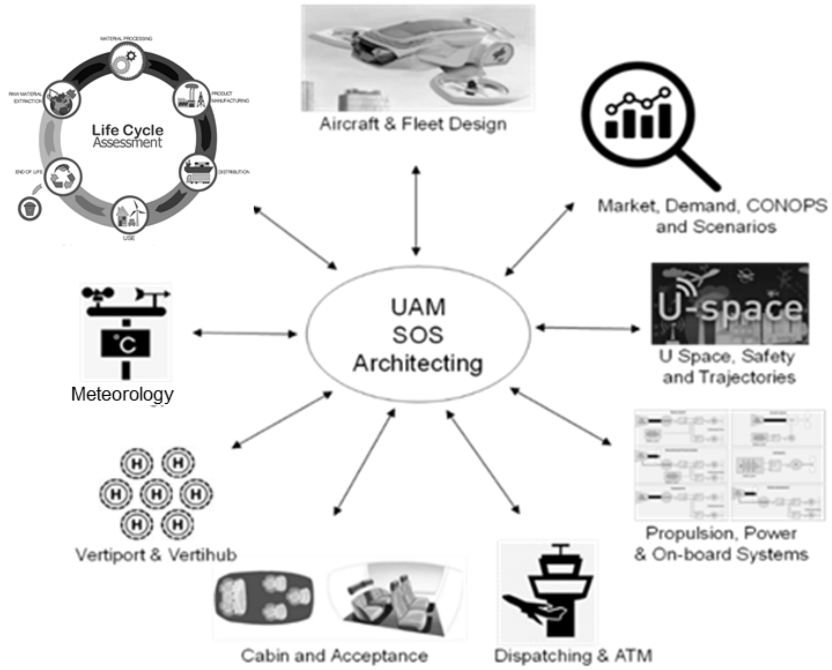

**Fig. 1 Urban Air Mobility as a System of Systems**

Vehicles of different capacity and architectures need to be designed considering Concept of Operations (CONOPS) for the use cases, the optimal combination of vehicles (fleet mixture) is essential to meet the UAM passenger and network demands. Furthermore, the energy required by the UAM system is an important element to be considered within the SoS. The choice of the propulsion sub-system does not only affect the design of the UAM vehicles, but also determines the re-energizing time of the vehicles. This time strongly impacts the operational throughput, i.e. the number of passengers transported in the UAM of the propulsion and recharging subsystem design is therefore an important parameter within the simulation driven design framework.

In addition, since many cities follow international or national sustainability policies regarding health and environmental aspects, it is expected that the sustainability of UAM systems will be of particular importance. This topic has not yet been sufficiently investigated by the scientific community, with only a few studies considering a life-cycle assessment of UAM concepts [6], [7]. In particular, this previous research has focused on identifying the environmental impacts produced during the production and operation phases of eVTOL (electric Vertical Takeoff and Landing) vehicles, considering future electricity mixes with sufficient renewable energy share. The methodologies proposed by the authors are limited in assessing the environmental impact of one single unit of the vehicles in terms of greenhouse gasses emissions (GHG). The work conducted by André and Hajek [6] dealt with three concepts for the aircraft mission (quadrotor, side-by-side and lift + cruise) and considered the UAM structure as well as an electric battery for the environmental assessment. On the other hand, Pinheiro-Melo et al. [7] presented an approach for a life-cycle assessment (LCA) on different cathode materials of an electric battery that powers an eVTOL aircraft. Both studies conclude that a sustainable operation of eVTOL aircraft in a future scenario is possible, as long as renewable energy is fed into the grid and advancements in battery chemistries, in order to achieve higher energy densities, are carried out. Therefore, a broader assessment of the environmental impacts of different propulsion systems based on two types of electric batteries with different chemistries that are operated with different electricity mixes are of particular interest within this study and are evaluated through an LCA. Since this study focuses on UAM as a SoS, the

LCA of the different UAM concepts needs to be conducted not only on a vehicle level, but also on a fleet level, which according to our review has not been performed before.

LCA is a methodology used to evaluate and analyze the environmental impacts of products or processes during their entire life cycle. This methodological framework is described by the ISO 14040:2006 [8] and ISO 14044:2006 [9] standards and has been widely accepted and validated by the industry and government agencies. The methodology takes into consideration material and energy flows of the studied systems and provides quantitative results that support the decision-making process in the design and engineering of new products, processes or services. An LCA with a cradle-to-grave approach considers the whole life cycle of a system, from the extraction of the raw materials for the manufacturing process to the recyclability and disposal strategies after the end of life (EoL). Thus, there are several categories that are used to characterize and quantify the environmental impacts, such as the global warming potential, human toxicity, terrestrial acidification, etc. Thereby, a common framework to be followed by LCA practitioners should include: the definition of a consistent scope and boundaries of the analysis, along with an adequate selection of the impact categories and a transparent interpretation and communication of the results [10]. This study places particular interest on the environmental impacts of the different propulsion systems, therefore the focus of the LCA also lies on these systems (batteries and electric energy for their operation). Since this study focuses on UAM as a SoS, the LCA of the different UAM concepts needs to be conducted not only on a vehicle level, but also on a fleet level.

Finally, the constituent systems in this UAM SoS (see Fig. 1) need to be orchestrated collaboratively. Even while designing and analyzing these constituent systems, collaborative aspects of design, such as domain interactions via a common language need to be considered. The SoS framework contains a tool chain across multiple DLR institutes located in different geographical locations and the domain analysis of different constituent systems is performed at different DLR institutes. This desires a collaborative IT framework [11].

Fig. 2 shows the System of Systems level, system level, and subsystem level. The System of Systems level evaluation involves a heterogeneous vehicle fleet, vertiports, the overall fleet level energy, average waiting times, mission success based on on-demand availability of the UAM vehicles, recharge times etc. The system-level design involves vehicle design and architecture (multirotor, lift + cruise, etc.). The subsystem level design involves power and propulsion subsystems. There are interactions between these levels. For example, the charging time depends on the propulsion subsystem, which will impact the vehicle design, and this further affects the mission time or operation speed, number of flights per recharge and waiting time.

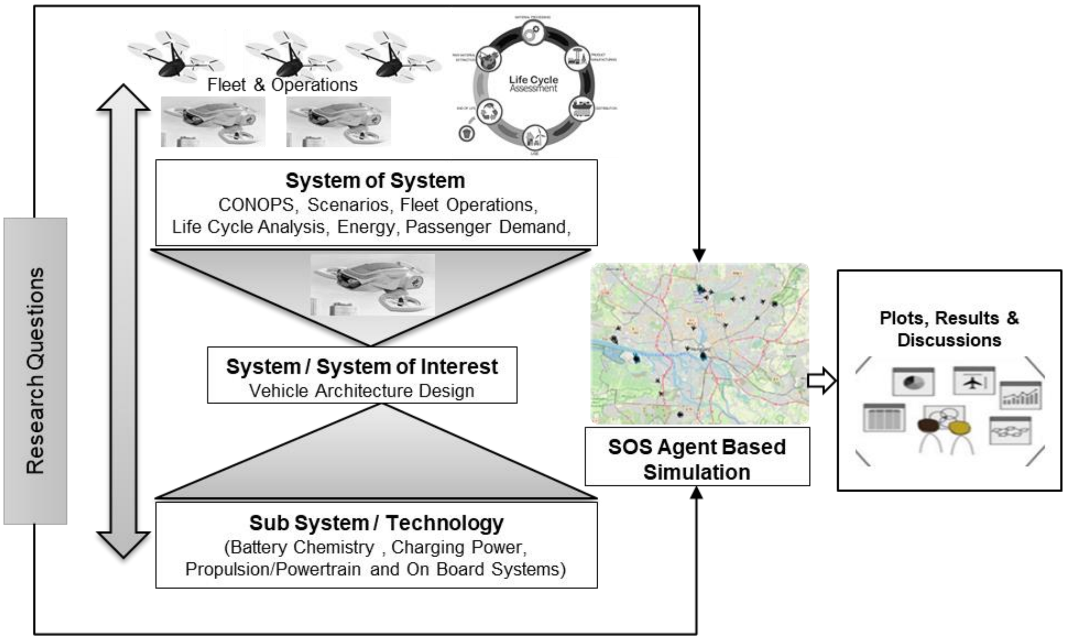

**Fig. 2 System of systems, system and subsystem levels**

## II. SoS Aircraft Design, Agent-Based Simulation, and Life-Cycle Assessment Framework

The System of Systems framework (see Fig. 3) describes the iterative approach of vehicle design and life-cycle assessment. Agent-based simulations play an important role, because for such homogeneous or heterogeneous vehicle operations and varying vertiport networks analytical methods cannot evaluate the interactions and emergence properties. Each vehicle is modeled as an agent having the properties of vehicles (aerodynamics, performance, propulsion subsystems) and each vertiport in the network is triggered by events. Once the vehicle is designed, the energy demand is analyzed at vehicle level. Additionally, a fleet is formulated in a vertiport network based on two chosen use cases (urban and suburban transport) and the fleet-level life cycle is evaluated. The demand at each vertiport is triggered by the passenger UAM requests as a demand distribution over a 24-hour duration as will be explained in Section II.B.

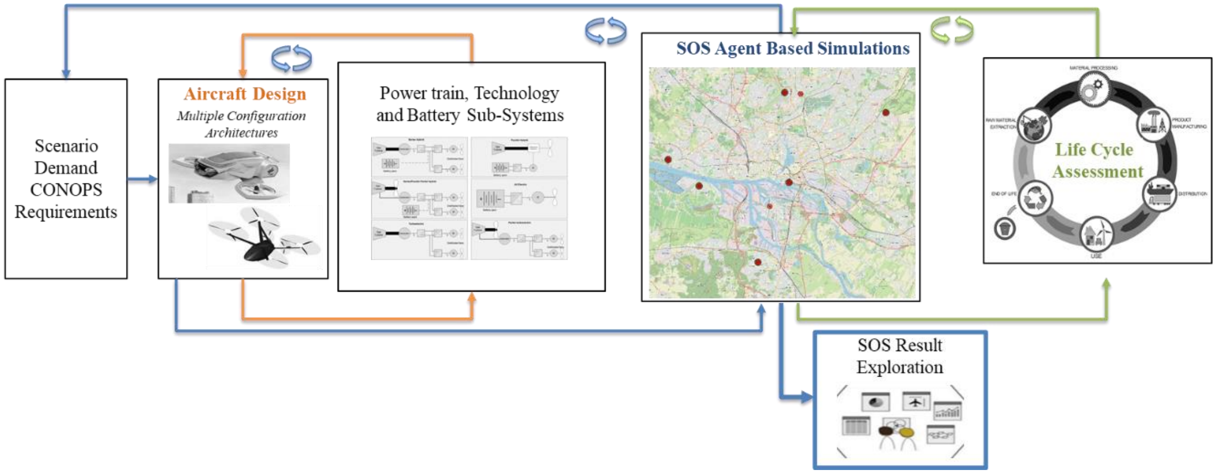

**Fig. 3 System of Systems framework**

### A. Aircraft Design and Performance

The aircraft design in this study process consists of conceptual eVTOL sizing and performance methods, where the open source software presented by Brown and Harris [12] is used. Their conceptual method is referring to McDonald and German [13], and thus utilizes momentum theory for vertical flight segments, i.e. hover flight, and simple steady flight relations for forward flight segments, i.e. cruising flight. Furthermore, a simple battery model is implemented, also known as 'energy in a box' model. Combining the efficiency of battery, power electronics, and motors, a total electric systems efficiency of 0.9 is assumed. In terms of aerodynamic efficiency, an induced power factor of 1.2 is applied for the hover performance. Furthermore, a propulsive efficiency of 0.8 is assumed, whereas it is only considered in forward flight. [12]

The underlying methodology requires certain configuration specific assumptions with regard to the UAM vehicles (see Table 1). In this study two different UAM vehicle configurations, i.e. multirotor and lift + cruise, are chosen for comparison. Regarding the general vehicle architecture, both are relatively simple configurations compared to other UAM vehicle concepts, e.g. vectored thrust configurations. Typical multirotor configurations allow for the installation of multiple rotors that provide lift in hover and forward flight. By the typically large rotor area, a low disk loading, i.e. aircraft weight divided by rotor area, can be achieved. Consequently, efficient hover flight is possible. However, the cruise performance is relatively poor. In contrast, a lift + cruise configuration, which basically is a fixed-wing cruise vehicle with additional rotors that provide lift in hover flight, is examined. Here, a comparably lower hover efficiency, but a higher cruise efficiency is typical for this UAM vehicle configuration.

Thereby, performance characteristics are estimated based on [13]. The disk loading of the UAM vehicle generally represents its hover efficiency, whereby a lower disk loading is favorable. With respect to cruising flight, the cruise speed and the associated lift-to-drag ratio are assumed. Hereby, a higher lift-to-drag ratio means higher cruise efficiency. While the assumptions generally follow [12] and [13], the cruise assumptions of the multirotor configuration are estimated more optimistically in reference to the sizing results of the quadrotor concept presented by Silva et al. [14].

Since the weight model of the aircraft consist of three items, i.e. empty weight, battery, and payload, an empty weight fraction based on the vehicle configuration is assumed. The multirotor configuration is a wingless vehicle, thus a lower empty weight fraction compared to the lift + cruise vehicle is assumed.

**Table 1  UAM vehicle characteristics**

| | UAM vehicle configuration | |
|---|---|---|
| Vehicle characteristics | Multirotor | Lift + Cruise |
| Disk loading $T/A$, N/m$^2$ | 120 | 500 |
| Cruise speed $V_{cr}$, km/h | 100 | 180 |
| Lift-to-drag ratio $L/D$ | 3.75 | 10 |
| Empty weight fraction $W_e/W_0$ (excl. battery) | 0.43 | 0.53 |

Apart from configuration specific characteristics, sizing mission requirements are set up based on the two use cases. Accordingly, two different sizing missions are considered in this study, which result in divergent sizing results depending on the UAM vehicle configuration. Both sizing missions consist of a single flight. The vertical take-off and landing segments are represented by hovering out of ground effect for a duration of 2 minutes each. Furthermore, a 20-minute loiter at minimum power conditions is assumed for the reserve segment. The mission profile for the sizing mission is shown in Fig. 4.

As this study compares urban and suburban UAM use cases, different cruise distances are assumed. In the case of a relatively short urban mission with a total cruise distance of 30 km, the hover efficiency may be more pronounced, hence rotary-wing cruise configurations, e.g. multirotor, may perform better. In contrast, the suburban use case, where a cruise distance of 70 km is required, may be more suitable for a fixed-wing cruise configuration, e.g. lift + cruise. The sizing payload is defined as either 2 or 4 persons on board (POB), which means that either a 2- or 4-seater is required, respectively. In the case of piloted operations, one seat is obviously occupied by the pilot, whereas, in the case of autonomous operations, one additional passenger seat becomes available. Independent of pilot or passenger, a mass of 90 kg is assumed per person. Regarding the sizing results, UAM vehicles with a Maximum Take-Off Mass (MTOM) greater than 3175 kg are not taken into consideration as per small-category VTOL aircraft certification requirements by European Union Aviation Safety Agency (EASA) [15].

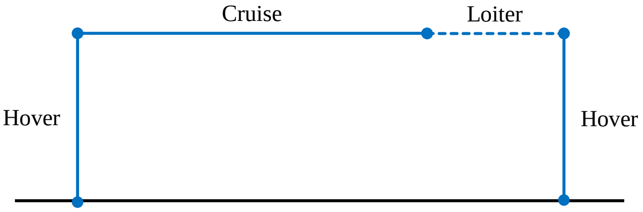

**Fig. 4  UAM vehicle sizing missions (cruise distances 30 km urban and 70 km suburban)**

Beyond the UAM vehicle and sizing assumptions, three battery chemistries, namely lithium nickel manganese cobalt oxide batteries (NMC-811 and NMC future) and lithium-sulfur (Li-S) batteries, are taken into consideration. In the initial time frame, an NMC-811 battery is anticipated, whereas the future time frame considers an advanced NMC battery. Additionally, a Li-S battery is regarded as a possible alternative. The fundamental battery characteristics, i.e. cell specific energy and lifetime, are assumed with reference to the battery technology roadmap published by Fraunhofer ISI [16]. All assumptions concerning the battery characteristics are summarized in Table 2. Therein, also fractions for battery pack integration, i.e. installation fractions, and fractions for the consideration of minimum and maximum depth of discharge, i.e. useable energy fractions, are given. In the context of this study, technology advances are assumed for both fractions.

**Table 2  Battery characteristics**

| | Time frame | | |
|---|---|---|---|
| Battery characteristic | 2025 | 2050 | 2050 |
| Chemistry | NMC-811 | NMC (future) | Li-S |
| Cell specific energy, Wh/kg | 350 | 500 | 600 |
| Installation fraction | 0.77 | 0.83 | 0.83 |
| Installed specific energy, Wh/kg | 269 | 417 | 500 |

| | | | |
|---|---|---|---|
| Useable energy fraction | 0.8 | 0.9 | 0.9 |
| Useable specific energy, Wh/kg | 215 | 375 | 450 |
| Cell mass per pack mass fraction | 0.62 | 0.75 | 0.75 |
| Lifetime, cycles | 500 | 1000 | 500 |

In order to prevent excessive battery degradation, a limit on discharge C-rate, i.e. battery capacity or energy per hour, is considered. Accordingly, a maximum of 3 C is allowed for the UAM vehicle sizing.

Finally, the aircraft performance is computed for all possible mission segments and load factors, again considering piloted as well as autonomous operations. Expanding on the simple mission definition for the UAM vehicle sizing, a more detailed mission profile is assumed and implemented in the ABS (see Fig. 5). The detailed definitions of the mission profile segments, which are numbered from 1 to 8, can be found in Table 3. Here, the power required is still a constant value for each segment, however, more different segments, e.g. vertical climb, transition, and cruise climb, are considered. At this stage of development, cruise descent is not yet implemented.

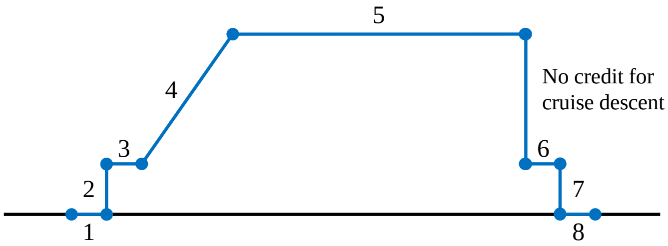

**Fig. 5 Mission profile for the UAM agent-based simulation**

Since the sizing mission performance is extended in the ABS, the vertical climb power $P_{\mathrm{vc}}$ is calculated according to momentum theory by

$$P_{\mathrm{vc}}=P_{\mathrm{h}}\left(\frac{V_{\mathrm{C}}}{2v_{\mathrm{h}}}+\sqrt{\left(\frac{V_{\mathrm{C}}}{2v_{\mathrm{h}}}\right)^2+1}\right) \tag{1}$$

where the hover power $P_{\mathrm{h}}$, the inflow velocity in hover $v_{\mathrm{h}}$ and the vertical climb speed $V_{\mathrm{c}}$ are required inputs that are available from sizing results and mission profile definitions. In terms of forward flight performance, a cruise climb segment is added. Consequently, the cruise climb power $P_{\mathrm{cc}}$ is calculated as follows:

$$P_{\mathrm{cc}}=\frac{WV_{\mathrm{cr}}}{L/D}+WV_{\mathrm{cr}} \tag{2}$$

As in the sizing mission performance, the cruise power $P_{\mathrm{cr}}$ is given by

$$P_{\mathrm{cr}}=\frac{WV_{\mathrm{cr}}}{L/D} \tag{3}$$

In order to model the transition from vertical to forward flight and vice versa, a linear acceleration at 0.2 $g$ is assumed. Thus, the transition time $t_{\mathrm{tr}}$ is calculated by

$$t_{\mathrm{tr}}=\frac{0.6\ V_{\mathrm{cr}}}{0.2\ g} \tag{4}$$

**Table 3 Mission profile segment definitions**

| Segment | Forward speed | Vertical speed, fpm | Altitude AMSL, ft | Distance | Time, min | Power |
|---|---|---|---|---|---|---|
| 1 Start up | – | – | 0 | – | 0.3 | 0.1 $P_{\mathrm{cr}}$ |
| 2 Vertical climb | – | 100 | 0 to 50 | – | 0.5 | $P_{\mathrm{vc}}$ |
| 3 Transition | 0 to 0.6 $V_{\mathrm{cr}}$ | – | 50 | – | $t_{\mathrm{tr}}$ | $P_{\mathrm{h}}$ |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 Cruise climb | $V_{cr}$ | 750 | 50 to 1500 | $D_{cc}$ | 2 | $P_{cc}$ |
| 5 Cruise | $V_{cr}$ | – | 1500 | $D_{req} - D_{cc}$ | $t_{cr}$ | $P_{cr}$ |
| 6 Transition | 0.6 $V_{cr}$ to 0 | – | 50 | – | $t_{tr}$ | $P_h$ |
| 7 Vertical descent | – | –100 | 50 to 0 | – | 0.5 | $P_{vc}$ |
| 8 Shut down | – | – | 0 | – | 0.3 | 0.1 $P_{cr}$ |

## B. Agent-Based Simulation

This section briefly explains the DLR in-house Agent Based Simulation (ABS) for analyzing a complex SoS. The development process and motivation behind the ABS framework is detailed in [17]. The UAM use case is built on top of the ABS framework and is composed of two main models: the demand model and the agent model with additional methods and classes implanted for additional features as in Fig. 6. The simulation framework was developed with an emphasis on modularity. As such, the capability to simulate any desired city, region, or country with ease is incorporated.

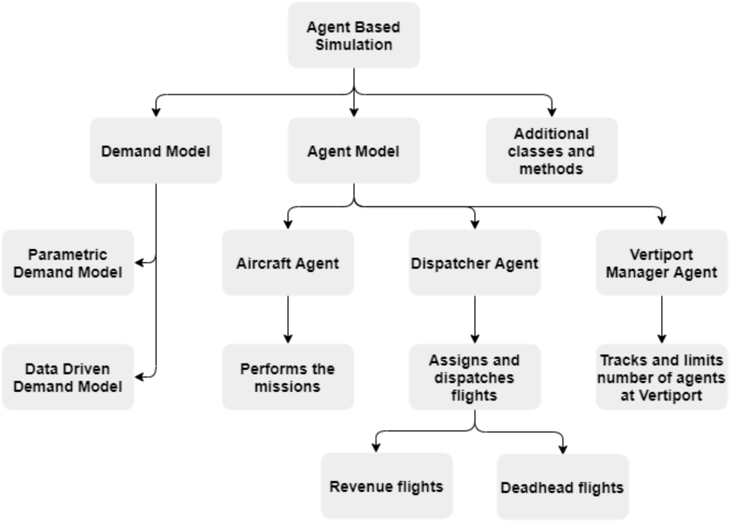

**Fig. 6 UAM agent-based simulation approach**

### 1. *Demand Model*

In the ensuing discussion, the term `demand` is used synonymously with passenger or mission. It is also used to refer to a single passenger demand or the overall demand of the network. A deadhead flight or mission is a non-passenger carrying flight flown to reposition the aircraft. The term `deadhead demand` therefore refers to a deadhead mission. In addition, a revenue flight or mission is a passenger carrying flight.

In the development of the parametric demand model as it is used in this study, special care was given to ensure it is modular and allows for quick modification of the demand model based on available data. The demand model consists of inflow and outflow curves defined at each vertiport. The inflow and outflow curves consist of multiple normal curves, which make up the desired distribution. The demand curves are described by the peak demand magnitude and the hour at which the peak occurs in addition to its standard deviation. In the current study, the standard deviation is kept constant at 2 hours. The outflow and inflow curve descriptions are then discretized into hour-long segments with their respective demand magnitudes evaluated at the middle of the hour-long segment.

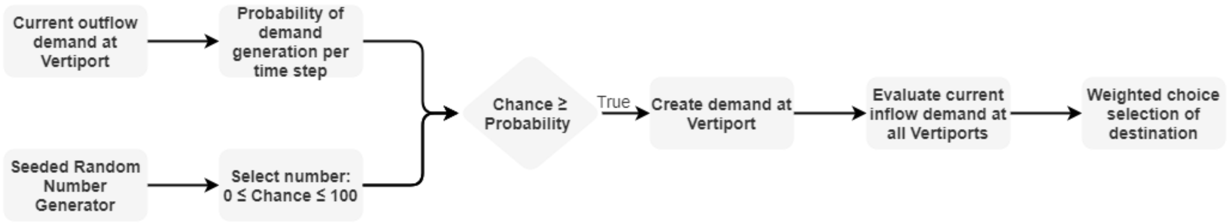

**Fig. 7 Demand generation logic**

Fig. 7 describes the logic behind the demand generation, which is applied at each iteration of the simulation for each vertiport. Initially, the value of the discretized outflow demand at the simulation time is retrieved and converted to a probability of demand generation per time step. This probability is then compared to a chance value selected by a seeded random number generator (RNG) between 0 and 100. If the chance is greater than the probability, a demand is generated at the vertiport. The destination of the generated demand is chosen by a weighted choice selection of the vertiports considering the inflow demand magnitudes at the simulation time for each vertiport. The demand generation uses an RNG to capture the randomness effect expected in real-life operations with passengers requesting flights in irregular time intervals. The RNG is seeded to ensure this randomness is deterministic and possible to recreate. From this point, the agent model is tasked with the assignment and dispatching of agents to fulfill the mission.

### 2. *Agent Model*

The agent model consists of the aircraft agents, the dispatcher agent, and the vertiport manager agents as previously shown in Fig. 6. The fleet definition consists of defining the number and characteristics of the aircraft agents. The cruise speed, passenger capacity, configuration, and performance are among the characteristics that can be defined for the aircraft agents. The fleet level definition consists of the size, and initial distribution of the aircraft agents. In this study, only homogenous fleets are considered and the deployment of heterogenous fleets is left for future studies.

The dispatcher agent assigns and dispatches the revenue as well as deadhead flights to the aircraft agents. The mission assignment is carried out using a bidding model in which each aircraft agent submits its bid for the mission in consideration. The dispatcher assigns each mission to the aircraft agent with the highest bid. The bidding model was developed with the aim of maximizing the percentage of successful missions and reducing the number of required deadhead flights by the assignment of each mission to the ideal aircraft agent based on the set criteria. After receiving a new demand, the dispatcher calls on all aircraft agents to place their bids, which consist of three parameters: the number of passengers assigned to the same mission, the estimated time of completion of the mission, and the available energy of the agent. In the computation of the estimated time of completion of the new demand, the agent considers the time needed to complete the active mission, if any, and any required charging time. The parameters considered in the bidding model are normalized by the time taken to fly the furthest distance between any two vertiports, the maximum passenger capacity, and the total battery capacity respectively. Each term in the bid equation is multiplied by a weighting factor, the weights of each term were chosen with an order of magnitude difference to represent the priorities set for the dispatching. Namely, the first priority is to maximize the load factor of the flights, secondly to reduce the wait time of the passengers and lastly to use aircraft with higher instantly available energy. Together with the normalization, the order of magnitude difference in the weighting ensures a hierarchical decision-making process in accordance with the dispatch priorities. The bid equation is as follows:

$$bid = w_1 \cdot \frac{n_{\text{assigned passengers}}}{n_{\text{passenger capacity}}} + w_2 \cdot \frac{t_{\text{mission completion}}}{t_{\text{longest route}}} + w_3 \cdot \frac{E_{\text{useable energy}}}{E_{\text{battery capacity}}}, \tag{5}$$

where $w_1 = 10$, $w_2 = 1$, and $w_3 = 0.1$.

Each aircraft agent can be assigned up to 2 missions at once, while the missions are carried out sequentially. Once an aircraft agent wins the bid and is assigned the mission, the mission is then allocated to one of these slots if possible. The allocation logic is described in Fig. 8. In this study, the deadhead demands are only generated once necessary: in the cases where the agent to whom the mission was assigned to is not in the same vertiport as the demand, a deadhead demand is dispatched to transport the agent to the required vertiport. The network imbalance requires non-revenue “deadhead” flights to re-distribute aircraft from the areas of low demand to areas of high demand [18].

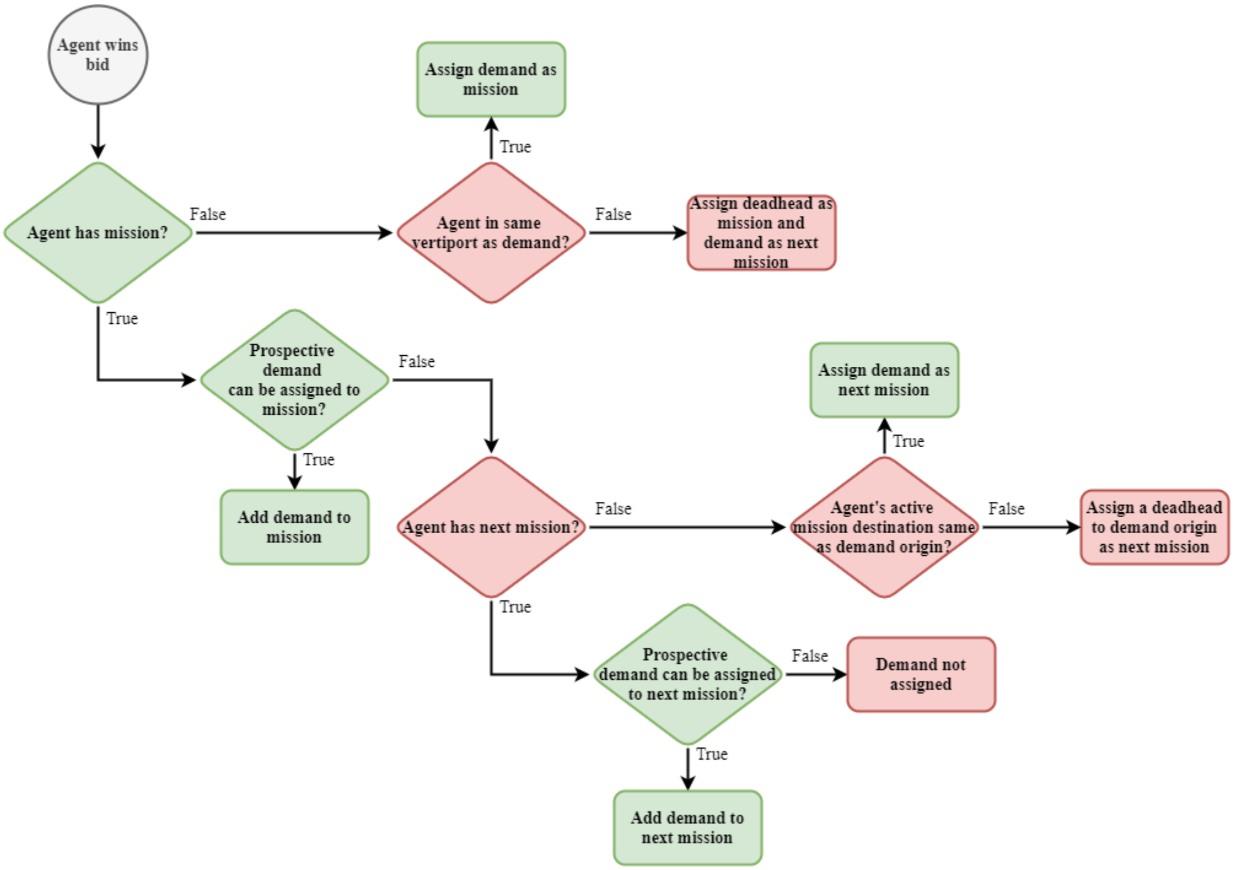

**Fig. 8  Logic for demand allocation to aircraft agent**

Once the mission is assigned, the aircraft awaits the dispatch decision from the dispatcher agent. If the assigned mission of the aircraft agent is a revenue mission, then the aircraft agent is dispatched when the dispatch criteria is satisfied. The dispatch criteria to satisfy is either the wait time of any demand assigned to the aircraft reaching the target wait time, or the aircraft agent reaching a load factor of 1. The aircraft agent is made to wait to allow for any possible additional demand to be assigned to it, thereby increasing the load factor. If the assigned mission is a deadhead mission, then the aircraft agent is dispatched immediately. In the special case that the agent is assigned a deadhead mission as its next mission and a revenue demand is generated for the same route as the deadhead prior to the dispatching of the deadhead mission, the revenue demand can be assigned to the scheduled deadhead mission, thereby allowing the operator to get revenue from the scheduled deadhead mission when possible. Lastly, the vertiport manager agent has two objectives: managing the number of agents at the vertiport and giving permission for takeoff and landing. In this study however, the limit on the vertiport capacity is not applied.

### 3. *Energy Model*

The energy model in the simulation tracks and updates the energy consumption and the re-energizing. From the sizing tool, the power consumptions for the revenue, deadhead and sizing missions are computed. The power consumptions of the revenue mission are computed for each possible load factor. Moreover, for both the deadhead and revenue missions, the powers associated with each mission segment is provided to the simulation from the sizing tool. In each iteration of the simulation, the available energy of the aircraft is updated based on its state of flight and its load factor. The simplifying assumption of constant power usage is assumed within each state of flight and load factor. In addition, the aircraft agents are assumed to charge their batteries at a constant rate defined by the charging power input when at a vertiport. Here, a charging efficiency of 0.9 is considered. All aircraft agents are assumed to start the simulation with a fully charged battery, that is the total battery capacity reduced by the usable energy fraction and energy required for the reserve mission.

### C. Life-Cycle Assessment

As described above, the vehicle design module sizes the propulsion system and energy carrier of the vehicles so that certain objectives can be met. For the use case modeled here, battery-electric propulsion systems with two different battery types are selected and compared: an NMC Li-ion battery and a Li-S battery. The energy requirements of the vehicles and subsequently the fleet can be determined for the different operational scenarios and urban environments based on the agent-based simulations. An LCA of the modelled UAM systems is conducted on fleet level with a focus on the energy used in order to analyze the environmental impacts. Thus, the system boundaries include the manufacturing of the batteries and the operation phase of the UAM vehicles considering the generation of the electricity needed to charge the batteries (see Fig. 9). The simulations also consider the expected lifetime of the batteries in terms of charge/discharge cycles in order to estimate the amount of battery packs needed throughout the lifetime of one vehicle. It is assumed that when reaching their expected lifetime in terms of cycles, the batteries are replaced by new ones. The manufacturing of the vehicles themselves, the end-of-life, and the infrastructure needed for re-energizing the vehicles are not considered as part of this study. The impact assessment is based on midpoint indicators as suggested by the International Life Cycle Data system (ILCD) scheme [10], [19], e.g. the global warming potential (GWP) and mineral resource scarcity.

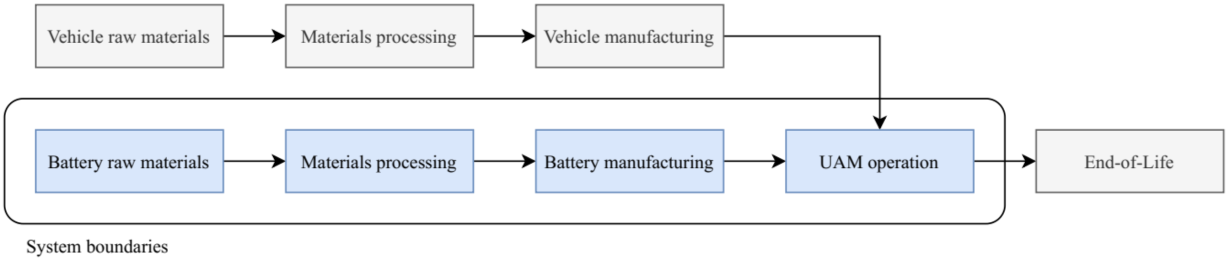

**Fig. 9 Schematic representation of the scope and boundary of the LCA. This study does not consider the manufacturing of the UAM vehicles and the end-of-life stage in the LCA of the UAM system.**

Some of the technical characteristics of the batteries used in the vehicles can be seen in Table 2. The inventory for the production phase of the NMC 811 Li-ion battery is based on the inventory for an NMC 622 Li-ion battery by Ellingsen et al. [20] and adapted using the bill of materials (BOM) published by Dai et al. [21]. The same inventory is used for the NMC battery in 2050 due to lack of data for this configuration. The SoS framework assumes however a higher specific energy and cycle count as listed in Table 2. The inventory for the Li-S battery is based on Deng et al. [22]. The battery pack masses are scaled up to match the ones used in the UAM vehicles. The background activities are taken from the ecoinvent 3.7.1 database. These two battery chemistries were chosen for the analysis because of their promising characteristics for a UAM application and due to the availability of detailed inventory data from literature.

In accordance with the scenarios for the operation of the UAM SoS, the two selected locations, namely Hamburg, Germany and San Francisco, California, USA, are also considered in the LCA of the fleet. For the evaluation of the system in the years 2025 and 2050 as modelled in the framework projections for electricity mix for the two locations are incorporated in the LCA. The data for the electricity mix in Germany corresponds to Scenario A in Pregger et al. [23] for an eighty-percent reduction in greenhouse-gas emissions by 2050. The GHG-Step Scenario based on the CA-TIMES framework from [24], [25] is used to model the mix in California. Here an eighty-percent reduction in greenhouse-gas emissions by 2050 compared to 1990 levels is modelled as well, but with a different underlying technology mix. The electricity mixes are modeled within the LCA using the respective processes from the ecoinvent database for the corresponding regions. Only the foreground system is modeled using the updated electricity mixes, i.e. the electricity used during the operation of the vehicles to charge the batteries and the electricity needed during the assembly of the battery cell and pack, thus assuming a local battery assembly. The background processes of the inventory (e.g. energy needed during raw material extraction or for the industries that provide the subcomponents of the batteries) were however not updated, since these activities are distributed throughout various world regions and a projection of these activities into the future bears a high degree of uncertainty.

The UAM system is assessed in terms of the transport service provided. Therefore, the LCA uses the passenger-kilometers travelled as a functional unit. The LCA is conducted using the open source framework Brightway2*. The impact categories that are used in the evaluation follow the ILCD recommendations [10] and are shown in Table 4.

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* https://brightway.dev/

The three resource-related indicators are to be used with caution according to the recommendation of the Institute for Environment and Sustainability of the Joint Research Centre of the European Commission [19]. An overview of the scope of the LCA is given in Table 5.

**Table 4 Overview of the ILCD impact categories used in the LCA**

| Impact category | Abbreviation | Unit | Level |
|---|---|---|---|
| Climate change (Global Warming Potential) | GWP | kg $CO_2$ eq | Midpoint |
| Freshwater and Terrestrial Acidification | FTAP | mol H+ eq | Midpoint |
| Freshwater Ecotoxicity | FETP | CTUe[*] | Midpoint |
| Freshwater Eutrophication | FEP | kg P eq | Midpoint |
| Marine Eutrophication | MEP | kg N eq | Midpoint |
| Terrestrial Eutrophication | TEP | mol N eq | Midpoint |
| Ionizing Radiation | IR | kBq U235 | Midpoint |
| Human Toxicity - Carcinogenic Effects | HTCE | CTUh[†] | Midpoint |
| Human Toxicity - Non-Carcinogenic Effects | HTNCE | CTUh | Midpoint |
| Ozone layer Depletion | ODP | kg CFC-11 eq | Midpoint |
| Photochemical Ozone Creation | POCP | kg NMVOC eq[‡] | Midpoint |
| Particulate matter/Respiratory inorganics | PM | Disease incidences | Midpoint |
| Resources - Minerals and Metals | MM | kg Sb eq | Midpoint |
| Resources - Dissipated Water | DW | $m^3$ water | Midpoint |
| Resources - Land Use | LU | soil quality index | Midpoint |

**Table 5 Overview of the LCA scope**

| | |
|---|---|
| Product / System | UAM fleet |
| Geographical boundaries | Germany and California (USA) |
| Temporal boundaries | 2025 and 2050 |
| Background data | Ecoinvent 3.7.1<br>LCI other studies (secondary data) |
| Allocation model | Cut off by classification |
| Software | Brightway2 |
| Functional unit | 1 passenger kilometer |

### D. Limitations of the UAM System of Systems Framework

This framework is the first attempt to evaluate the UAM use case from Subsystem over System of Interest to the System of Systems level and evaluate the impacts on the Life-Cycle Analysis. Currently, there are certain limitations:

1. The framework assumes homogeneous fleets, where each aircraft agent is of the same type and characteristics, e.g. cruise speed, payload, etc. The capability of simulating heterogeneous fleets exists, but the dispatch and deadhead modelling needs to be optimized.
2. The framework assumes pseudo passenger demand and unlimited vertiport landing pads and parking/gate capacity. A realistic UAM passenger demand can be included when there is a broader study of market and vertiports. The limited landing pads and parking capacity will require further optimization with regard to dispatching.
3. The trajectories assumed between vertiports is a simple direct flight consisting of the mission segments, as shown in the mission profile in Fig. 5. Ideally, the trajectories should be modelled considering driving factors such as noise disturbances and airspace clearances among others, i.e. modelled closer to what is expected in reality.
4. The underlying aircraft design methodology is limited by simply assuming fixed values for each aircraft architecture, i.e. disk loading, lift-to-drag ratio, and empty weight fraction. Thus, future work will focus on a more sophisticated modelling of aerodynamics and weights with respect to different UAM aircraft architectures. Accordingly, initial steps have already been taken in another study published at this conference [26].

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[*] CTUe: Comparative Toxic Unit for ecosystems

[†] CTUh: Comparative Toxic Unit for humans

[‡] NMVOC: Non-Methane Volatile Organic Compound

## III. Case Study

To evaluate the SoS framework in combination with the LCA, a case study analysis is carried out. Thereby, two geographic scenarios are considered. The examined use cases focus on urban operations (City of Hamburg, Germany and San José, CA, USA) with an average mission range of 15 km and suburban operations (Hamburg Metropolitan Region, Germany and San Francisco Bay Area, CA, USA) with an average mission range of 40 km. In order to evaluate the UAM SoS for any given city, the market or passenger demand is needed. Since there is no extensive study available and considering the inherent uncertainty of the market adoption of UAM, the authors decide to assume a demand which is parametric and changeable for any new inputs of demand data. Furthermore, the vertiport locations should be derived based on the city topography, demand, and intermodal transport. The vertiport locations are assumed for this current study and can be easily varied in the framework using latitude and longitude coordinates when the study is updated with market studies. Consequently, Fig. 10 and Fig. 11 show the demand distribution at six vertiports, both assumed, for the City of Hamburg in Northern Germany, and the San Francisco Bay Area in the United States of America, respectively. Besides the geographic scenarios, temporal assumptions are taken into consideration. Here, several technology advancements, starting from market entry in 2025 until market expansion in 2050, are assumed and their impact on the SoS performance and the LCA is investigated. A summary of the most relevant case study parameters is provided in Table 6.

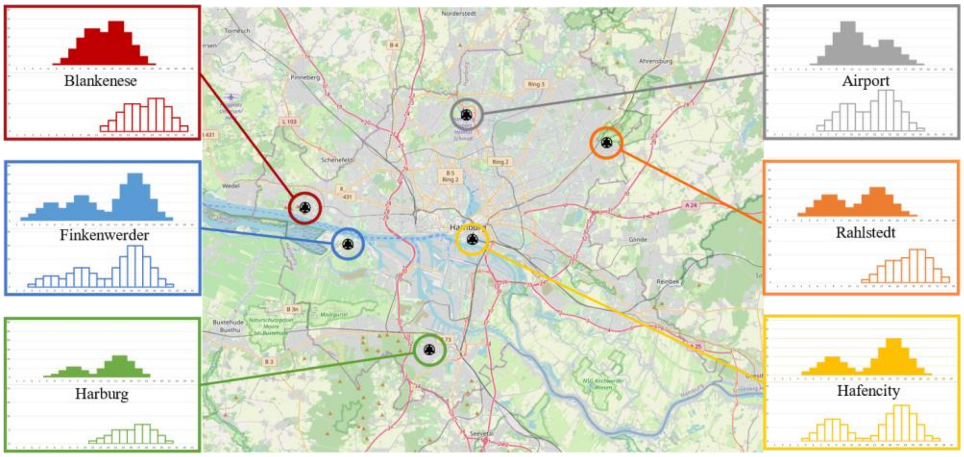

**Fig. 10 UAM use case for Hamburg, Germany, showing vertiport locations and corresponding demand distributions (outflow in solid color, inflow with no fill)**

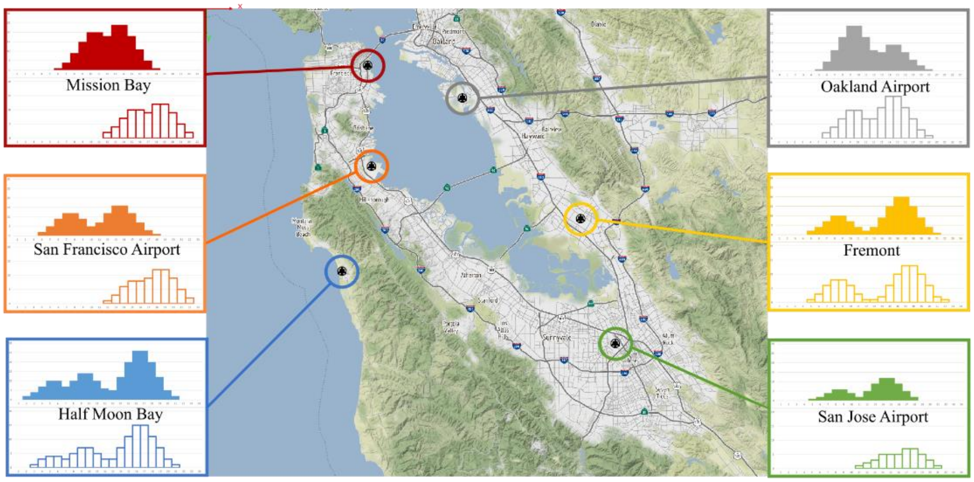

**Fig. 11 UAM use case for San Francisco, USA, showing vertiport locations and corresponding demand distributions (outflow in solid color, inflow with no fill)**

In addition to the battery discharge characteristics introduced in Section II, the battery charging during turnaround is either limited by the maximum charging C-rate or the charger power, which is available at the vertiport. In 2025, an optimistic maximum of 2.5 C is allowed, whereas, in 2050, 4 C are assumed to be feasible. This means that, in 2025, the battery can be fully charged within 24 minutes by fast charging. In 2050, the fast charging at a maximum of 4 C leads to a charging time of 15 minutes. This enables short turnarounds and, therefore, facilitates achieving a high percentage of successful missions, which will be explained in the following paragraph. Such high C-rates can only be realized with a sufficient charger power at the vertiports. In 2025, only a maximum of 400 kW might be available, which may limit the charging C-rate of some vehicles. The assumption of 1000 kW with regard to the future time frame in 2050 certainly allows fast charging for all vehicles.

Regarding the lifetime of the UAM vehicles, assumptions based on flight hours are made. With reference to Brown and Harris [12], a vehicle lifetime of 10,000 flight hours is adopted initially, whereas an advancement up to 15,000 flight hours is estimated for the future time frame.

The success criteria considered for the mission is the wait time of the passengers compared to the target wait time. In this study, the target wait time is defined as 15 minutes, which means that each passenger waiting more than 15 minutes results in a failed mission. This value is set allowing enough time for the passenger to reach the vertiport from their location through other modes of transport. The percentage of successful missions is used as the primary factor for gauging the success of the SoS, and is hereby referred to as the success percentage.

A total of 450 cases (90 design points on 5 different seeds) were simulated in this DoE and particular trends are shown in the following results in Chapter IV.

**Table 6 Summary of the case study parameters**

| | Time frame | | |
|---|---|---|---|
| Case study parameter | 2025 | 2050 | 2050 |
| Use cases | Urban, suburban | | |
| Geographic locations | Hamburg (Germany), San Francisco Bay Area (USA) | | |
| Vehicle configurations | Multirotor, lift + cruise | | |
| Reserve requirement | 20-minute loiter | | |
| Persons on board | 2, 4 | 4 | 4 |
| Vehicle lifetime, flight hours | 10,000 | 15,000 | 15,000 |
| Revenue mission piloted? | True | False | False |
| Deadhead mission piloted? | False | False | False |
| Battery chemistry | NMC-811 | NMC (future) | Li-S |
| Battery useable specific energy, Wh/kg | 215 | 375 | 450 |
| Battery lifetime, cycles | 500 | 1000 | 500 |
| Battery max. charging C-rate, 1/h | 2.5 | 4 | 4 |
| Charger power available, kW | 400 | 1000 | 1000 |
| Passenger demand | Distributions scaled to a maximum of 48 revenue passengers per hour | | |
| Homogeneous fleet size | 12, 18, 24, 30, 36, 42, 48, 54, 60, 66, 72, 78, 84, 90, 96 | | |
| Vertiport capacity | 100 (see Section II) | | |
| Target wait time, min | 15 | | |

The SoS evaluating parameters shown in the results of this study are explained in the following:

- Revenue Passenger Transported – Total number of passengers transported in a given 24-hour day
- Wait Time – Elapsed time from demand creation in the simulation until take-off
- Average Wait Time – Average wait time of all revenue passengers
- Success Percentage – Percentage of revenue passengers waiting less than target time of 15 minutes
- Deadhead ratio – Ratio of deadhead flights (non-passenger carrying flights) to passenger (revenue) flights
- Load Factor – Average load factor of all revenue and deadhead flights (computed excluding the pilot)
- Energy used by network – Total energy used by the UAM SoS or network
- Pax-km – Sum over the fleet lifetime of the product of passengers carried by distance flown for each mission

## IV. Research Questions, Results, and Discussions

As shown in Fig. 12 below, the result sections, observations made during this multilevel approach containing: SoS driven UAM vehicle design, battery technologies, fleet combinations, operational effects, and life-cycle assessment are expressed by several research questions and discussions. While some are from the point of view of the SoS, others are from SoI perspective. Moreover, sensitivities of aircraft design performance change due to battery chemistry change such as NMC and Li-S, energy consumed, and operations are considered. The life-cycle assessments were performed for each of the vehicle, technology and operation combinations. Each of the below questions emphasizes the need for analyzing UAM from a holistic SoS perspective.

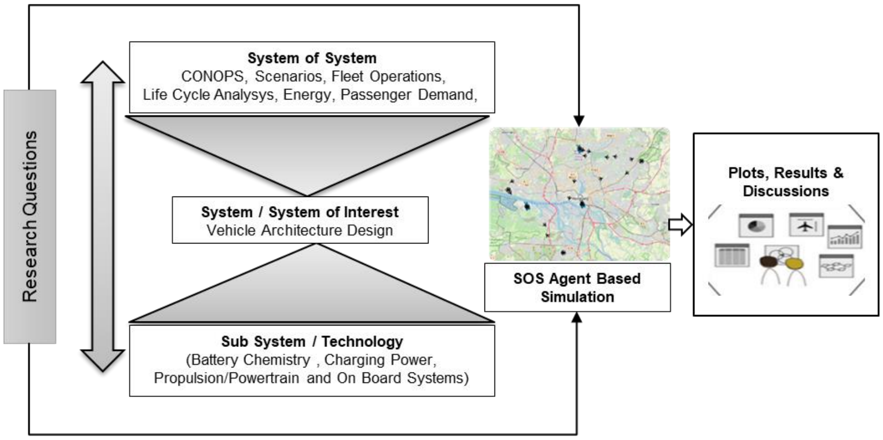

**Fig. 12 Research Questions across Multiple Levels**

The SoS research questions addressed in this study are as follows:

1) What is the impact of autonomy on the UAM fleet and the UAM LCA?
2) What is the impact of different geographic locations on the UAM LCA?
3) What is the impact of different vehicle passenger capacities on the UAM fleet and on the UAM LCA?
4) What is the impact of different use cases on the UAM fleet and the UAM LCA?
5) What is the impact of different technology time frames on the UAM fleet and the UAM LCA?
6) What is the impact of different battery chemistries on the UAM fleet and UAM LCA?

### A. Aircraft Design (System of Interest) Results

Regarding the aircraft design results for the multirotor as well as the lift + cruise configuration, all designated vehicles converged and also meet the earlier mentioned EASA certification criteria relating to MTOM (see Section II). Subsequently, the sizing results are presented together with the underlying sizing requirements.

Table 7 summarizes the data for the multirotor configurations in 2025 and 2050. It is important to note that, even though the payload is increased from 2 to 4 POB, the MTOM of the multirotor drops significantly for both advanced batteries in 2050. This is an expectable trend for electric aircraft, where the battery mass, and thus, the MTOM reduces because of the higher battery specific energy. Due to a 20% higher battery specific energy, the multirotor equipped with a Li-S battery results in an 8% lighter MTOM compared to the multirotor vehicle that has an advanced NMC battery installed.

**Table 7 Sizing requirements and results of the multirotor configuration**

| | Time frame | | |
|---|---|---|---|
| Vehicle parameter | 2025 (NMC) | 2050 (NMC) | 2050 (Li-S) |
| Cruise distance, km | 30 | 30 | 30 |
| Cruise speed, km/h | 100 | 100 | 100 |
| Persons on board | 2 | 4 | 4 |
| Maximum take-off mass, kg | 986 | 967 | 889 |
| Airframe mass, kg | 424 | 416 | 382 |
| Battery mass, kg | 382 | 191 | 146 |

| | | | |
|---|---|---|---|
| Payload mass, kg | 180 | 360 | 360 |
| Battery energy, kWh | 82.3 | 71.8 | 65.9 |
| Hover power, kW | 103.6 | 101.7 | 93.4 |
| Cruise power, kW | 99.3 | 97.4 | 89.5 |
| Hover C-rate, 1/h | 1.3 | 1.4 | 1.4 |
| Cruise C-rate, 1/h | 1.2 | 1.4 | 1.4 |
| Charger power, kW | 228.6 | 319.1 | 292.9 |
| Charging C-Rate, 1/h | 2.5 | 4 | 4 |

Furthermore, Table 8 summarizes the sizing requirements and results for the lift + cruise vehicles in 2025 and 2050. Generally, similar trends as for the sizing results of the multirotor configuration are found. Additionally, it should be noted that the battery sizing of the first lift + cruise vehicle in Table 8 (2 POB, 30 km cruise distance) is driven by the discharge C-rate limitation (see Section II). This is due to the comparably high disk loading of the UAM vehicle, which leads to a high battery power demand in hover flight. Apart from that, the turnaround procedures of third lift + cruise vehicle in Table 8 (4 POB, 70 km cruise distance) may be limited as the required charger power for fast charging at 2.5 C exceeds the priorly defined limit of 400 kW. Thus, the available charger power of 400 kW only allows for charging at 1.6 C.

**Table 8  Sizing requirements and results of the lift + cruise configuration**

| | Time frame | | | | |
|---|---|---|---|---|---|
| Vehicle parameter | 2025 (NMC) | 2025 (NMC) | 2025 (NMC) | 2050 (NMC) | 2050 (Li-S) |
| Cruise distance, km | 30 | 70 | 70 | 70 | 70 |
| Cruise speed, km/h | 180 | 180 | 180 | 180 | 180 |
| Persons on board | 2 | 2 | 4 | 4 | 4 |
| Maximum take-off mass, kg | 1119 | 1462 | 2923 | 1229 | 1117 |
| Airframe mass, kg | 593 | 775 | 1549 | 651 | 592 |
| Battery mass, kg | 346 | 507 | 1014 | 218 | 165 |
| Payload mass, kg | 180 | 180 | 360 | 360 | 360 |
| Battery energy, kWh | 74.5 | 109.2 | 218.4 | 81.6 | 74.2 |
| Hover power, kW | 223.6 | 292.0 | 584.1 | 245.6 | 223.1 |
| Cruise power, kW | 89.2 | 99.6 | 199.3 | 83.8 | 76.1 |
| Hover C-rate, 1/h | 3 | 2.7 | 2.7 | 3 | 3 |
| Cruise C-rate, 1/h | 1.2 | 0.9 | 0.9 | 1 | 1 |
| Charger power, kW | 206.9 | 303.3 | 400 | 362.7 | 329.8 |
| Charging C-Rate, 1/h | 2.5 | 2.5 | 1.6 | 4 | 4 |

Since the mission profile is modeled in more detail in the ABS, an exemplary power curve, i.e. battery power over mission time, is shown in Fig. 13. Here, both shown UAM vehicles are sized with respect to the NMC-811 battery characteristics in 2025. The sizing mission considers the urban use case, where 2 POB and a cruise distance of 30 km are required. Thereby, the power curve in Fig. 13 refers to a 20 km cruise mission with full payload. As explained in the underlying methodology (see Section II), it can be seen that the power demand in vertical climb and transition is higher for the lift + cruise configuration, whereas the power demand in forward flight is higher for the multirotor. Due to the higher cruise speed of the lift + cruise vehicle, its resulting block time is shorter by approximately 5 minutes or 36% compared to the multirotor.

Even though the required battery power of the multirotor is higher in the ABS performance model compared to the sizing performance model, the discharge C-rate is still found to be clearly below the earlier defined maximum of 3 C. Furthermore, largely enough energy is stored in the battery to perform all the missions as required for the SoS case study scenarios.

Since the required battery power in the case of the lift + cruise vehicle is higher in vertical climb compared to hover flight, the battery is actually discharged at a slightly higher C-rate compared to the previously defined limit of 3 C in the sizing mission. However, this behavior only happens in the cases where the vehicle sizing is primarily driven by the battery specific power, i.e. hover C-rate approaching the limit of 3 C, which only occurs for this particular vehicle in 2025. Still, the duration during which the excessive C-rate will be required is kept short at 30 seconds per vertical climb or descent segment. Furthermore, the burst discharge C-rate is definitely above the assumed limit for battery protection. Regarding the technology scenario in 2050 it may be assumed that advanced batteries will allow for higher C-rate discharges, thus maintaining battery health despite discharging beyond a C-rate of 3 C at times.

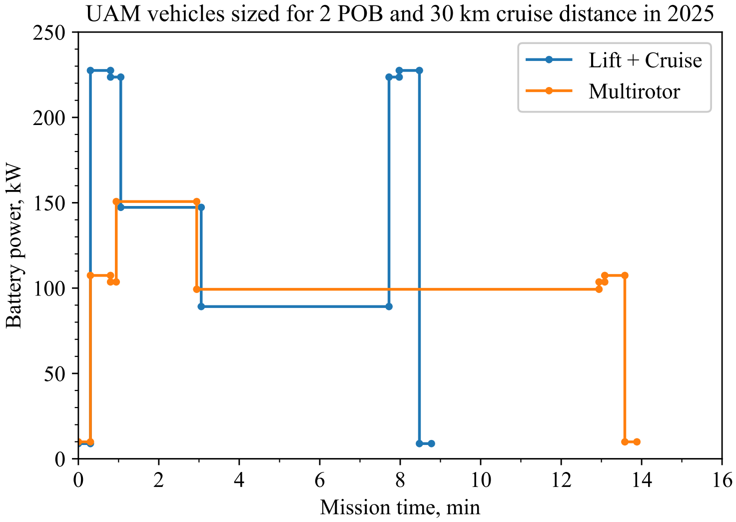

Fig. 13 Exemplary battery power curves for a 20 km cruise mission in the agent-based simulation

## B. UAM Fleet (System of Systems) and Life-Cycle Assessment Results

### 1. *What Is the Impact of Autonomy on the UAM Fleet and the UAM LCA?*

| Time Frame | Use Case | Vehicle | Capacity | Battery | Operations |
|---|---|---|---|---|---|
| 2025 | Hamburg: Urban | Multirotor | 2 POB | NMC-811 | **Piloted vs Autonomous** |

In this question, the effect on the SoS and LCA of fully autonomous flights vs piloted flights are investigated. In the latter case, only deadhead flights are assumed to be operated autonomously, whereas all operations are autonomous in the former case. Fig. 14 shows the fleet size versus the Measures of Effectiveness (MoE) of UAM SoS. For the Autonomous fleet, 48 aircraft could successfully cater to 90% of the missions within 15-minute wait time limit whereas for the piloted fleet, 78 aircraft are needed. This difference is due to the fact that, the autonomous vehicles can carry up to 2 passengers on board whereas piloted can only carry 1 passenger apart from the pilot. The piloted fleet requires 75% more aircraft compared to autonomous fleet to cater same number of passengers within 15-minute success criteria. The autonomous fleet required 0.579 kWh/pax-km compared to 1.014 kWh/pax-km, a 40% reduction on energy consumed per pax-km.

The impact of the fleet size on the deadhead ratio is also visualized. Deadheading is a necessary burden in the UAM SoS, resulting from a vehicle availability vs passenger flight demand mismatch at the vertiports. In such cases, the simulation reallocates an aircraft to the needed vertiport. Often, when the fleet size is small, the need for deadhead can harm the SoS performance as larger portions of the fleet have to be used for repositioning. Thus, the reason for low success percentage at lower fleet size is partly due to fleet re-organization.

Fleet Total Energy provides the energy required by autonomous and non-autonomous fleet and it can be seen that, as the fleet size increased there is an energy peak (corresponding to fleet sizes with maximum deadhead flights). This peak also corresponds to the fleet size at which all passengers are able to be served. As fleet size is increased beyond this point, the number of deadhead flights required decrease. It is worth note that at the lower fleet sizes, the fleet is unable to serve all the generated demand as can be seen from the number of revenue passengers. As the fleet size is increased, the deadhead ratio decreases and stabilizes. This similar trend is seen in the total network energy and energy per pax-km. Average wait time is an important metric, within the success or fail criteria, it can be understood how the system is clogged, with larger average wait times indicating the inability of the fleet to serve the demand.

The impact of autonomy on the fleet/SoS level is significant, ranging from the number of aircraft required to attain a desired success rate to the energy consumed by the respective fleets. These results at the SoS level are then propagated to the LCA by the energy consumed at fleet level, total distances flown, passengers transported, and battery technology assumptions. The LCA is performed for the entire fleet and entire distances travelled with respect to operations throughout the entire lifetime of the UAM fleet. The results are provided in Fig. 15.

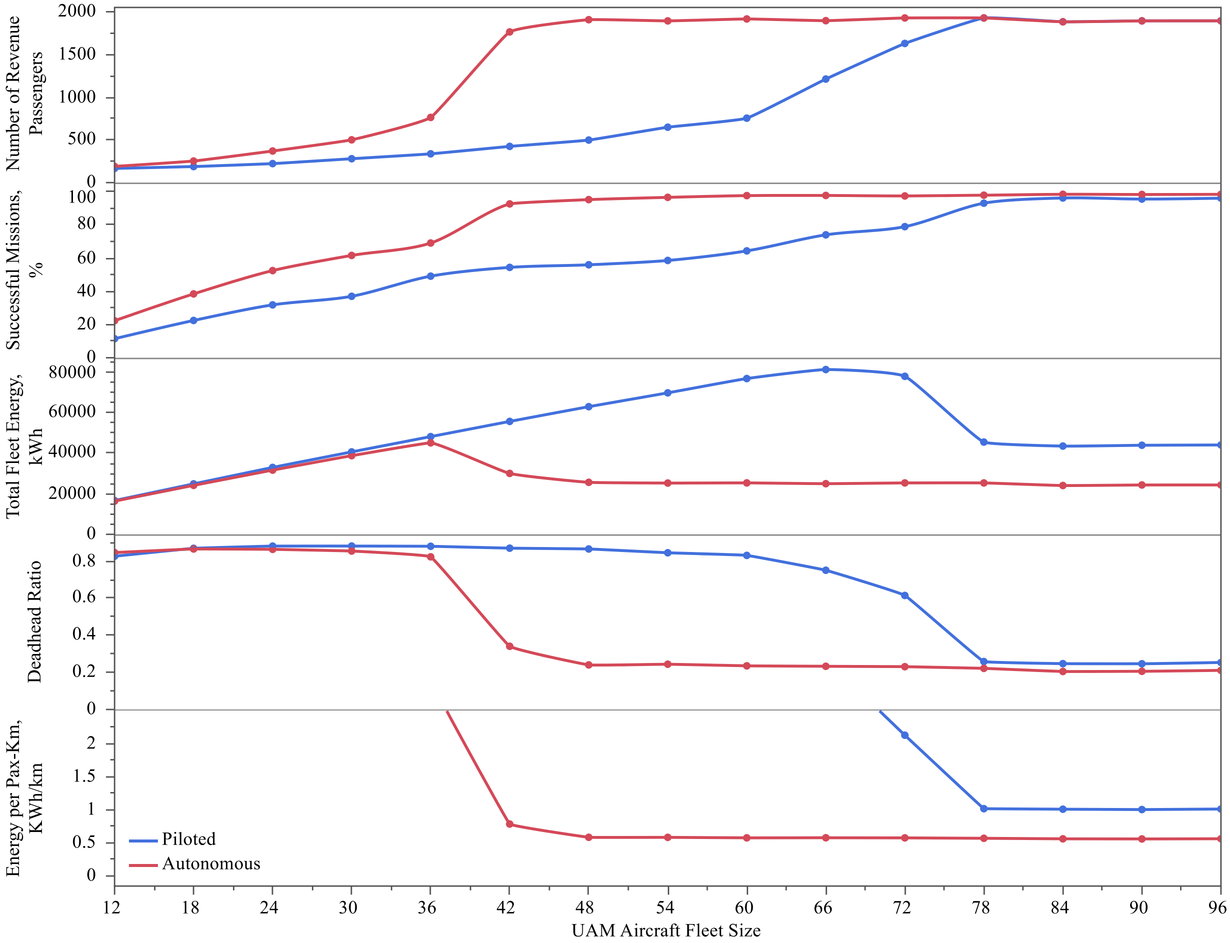

**Fig. 14 SoS comparison of the two UAM fleets for a piloted vs autonomous scenario in 2025.**

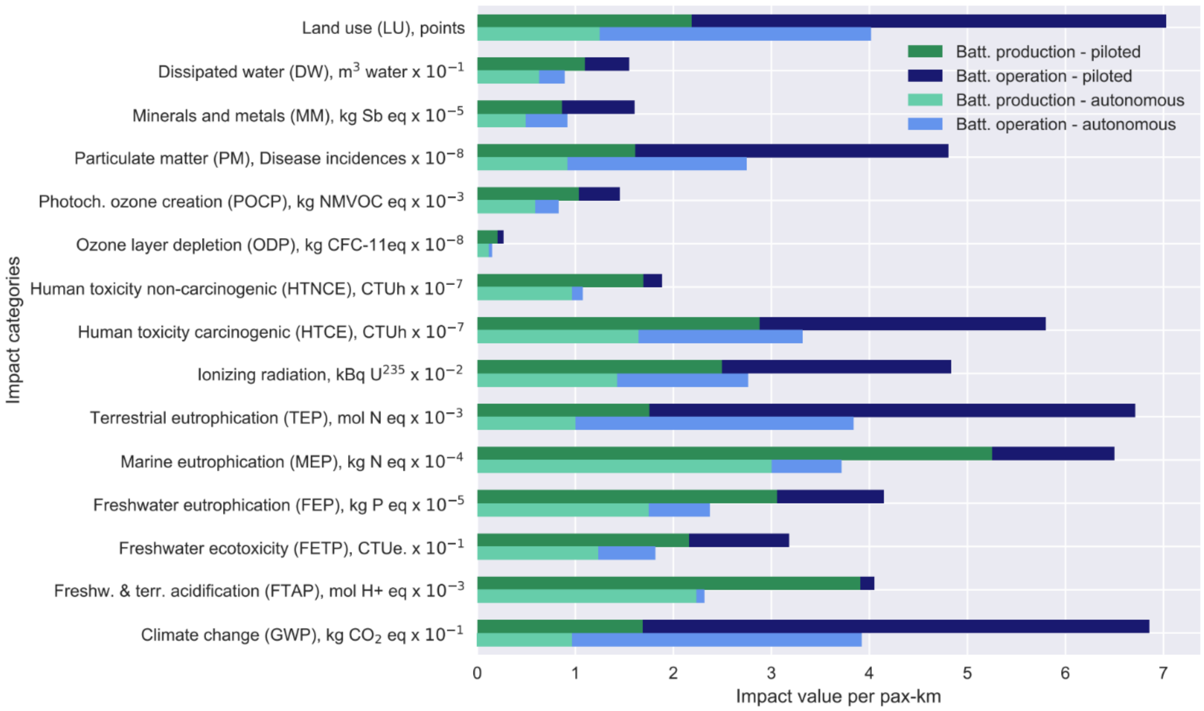

**Fig. 15 LCA of the two UAM fleets for a piloted vs autonomous scenario in 2025.**

A clearly lower impact especially for the operation phase of the batteries in terms of the impacts per passenger-kilometer can be seen for the autonomous vehicle compared to the piloted one, as expected. The impacts from the battery production are also lower since the autonomous vehicle carries two passengers in contrast to the piloted vehicle that carries one passenger (plus the pilot).

### 2. *What Is the Impact of Different Geographic Locations on the UAM LCA?*

| Time Frame | Use Case | Vehicle | Capacity | Battery | Operations |
|---|---|---|---|---|---|
| 2025 | **Urban: Hamburg vs California** | Multirotor | 2 POB | NMC-811 | Piloted |

The best fleet required to cater to 90% of passenger demand for both urban use cases in Hamburg and San José, California autonomous fleet is 78 UAM vehicles. The energy consumed for operating in both cities is similar due to same number of vertiport, same assumed demand and same distances between vertiport. It was set up this way, since the authors were interested to evaluate the effect of life-cycle analysis in two geographic locations. The LCA results are provided in Fig. 16.

Here it can be seen that during the operation phase the UAM fleet in Hamburg has a higher GWP, FEP, MEP, TEP compared to the case in San Francisco, as the electricity in 2025 Germany has a much higher percentage in coal-based energy. The higher land use (LU) impact for Germany is due to the higher percentage of biomass used in electricity generation. The higher ODP impact in California stems from the higher natural gas share in the electricity mix.

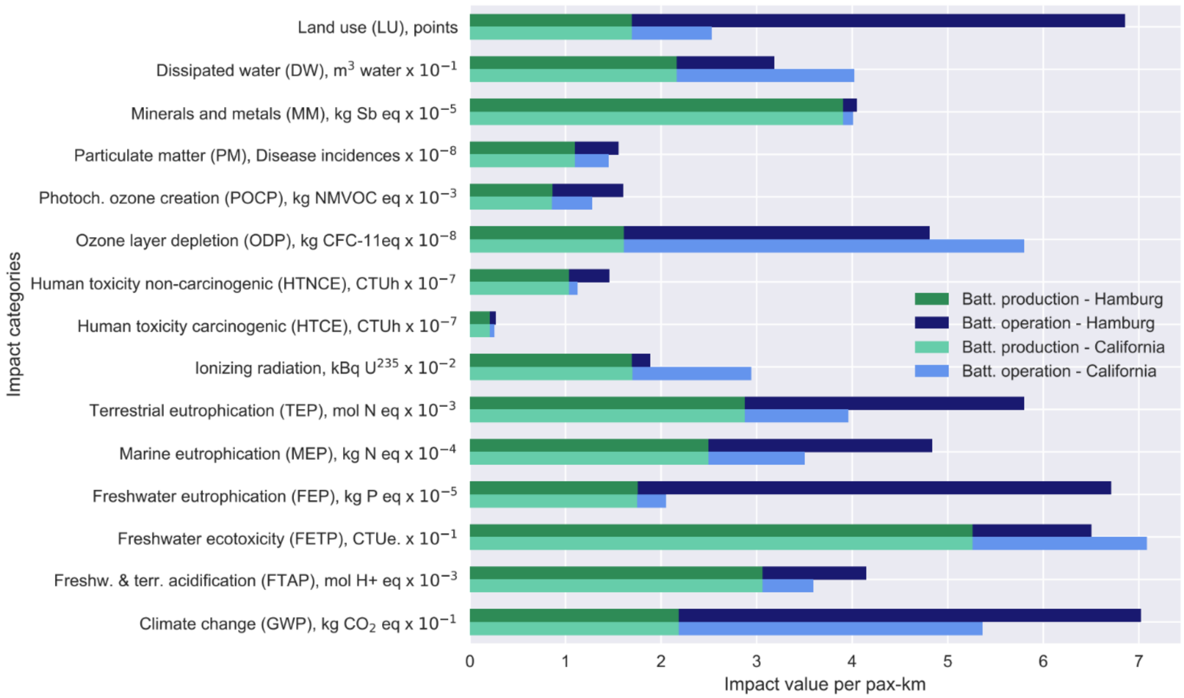

**Fig. 16 LCA of two UAM fleets for Hamburg urban vs California urban in 2025.**

### 3. *What Is the Impact of Different Vehicle Passenger Capacities on the UAM Fleet and on the UAM LCA?*

| Time Frame | Use Case | Vehicle | Capacity | Battery | Operations |
|---|---|---|---|---|---|
| 2025 | Hamburg: Suburban | Lift + Cruise | **2 vs 4 POB** | NMC-811 | Piloted |

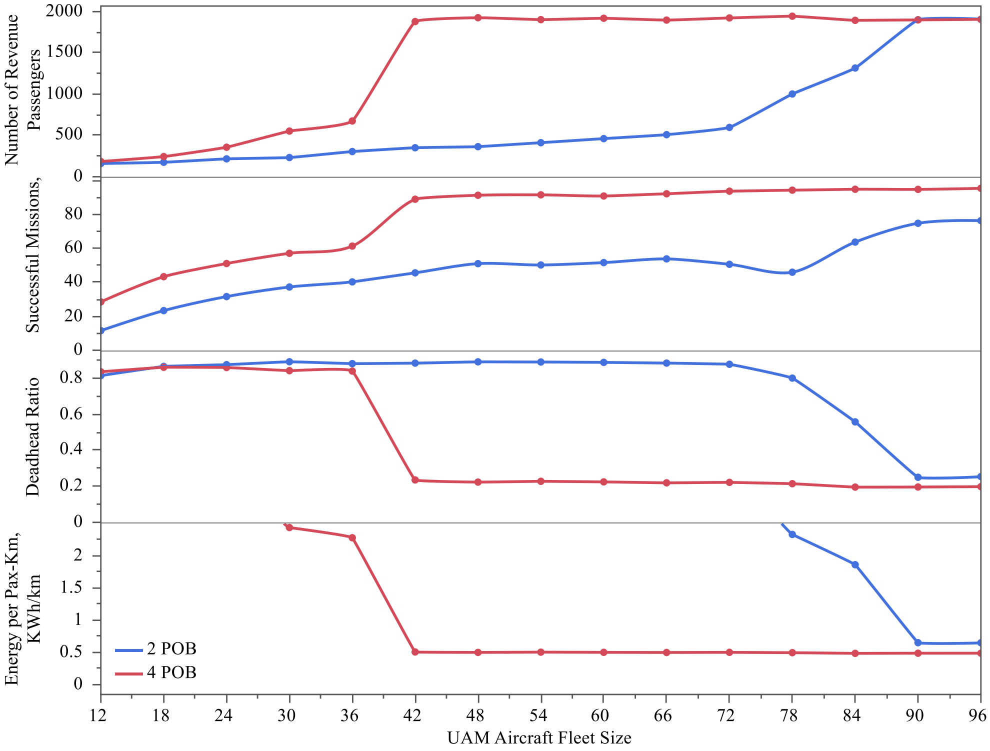

**Fig. 17 SoS comparison of the two UAM fleets with 2 persons on board vs 4 persons on board.**

From a Fleet perspective, the impact of passenger capacity is very significant. For the fleet composed of aircraft with a capacity of 2 persons on board, 90 aircraft are required to achieve a success rate of 75%, whereas for the fleet of aircraft with a capacity of 4 persons on onboard, only 42 aircraft are needed as can be seen from Fig. 17. In order to achieve a success rate of 90%, an even larger fleet size would be required. Moreover, from the number of revenue passengers it can be seen that for the 2 POB fleet, 90 aircraft are required to even be able to transport all the passengers, whereas for the 4 POB fleet only 42 aircraft are needed. The complexity of the UAM system can be seen in this result, by tripling the revenue passenger capacity (1 revenue passenger vs 3 revenue passengers) the fleet required is only slightly more than halved. This behavior is owing to the fact that the average load factor for the 4 POB fleet is not 1 meaning that the aircraft are not always fully utilized.

The energy by fleet with 2 POB is 0.646 kWh/pax-km compared to 0.501 kWh/pax-km for 4 POB

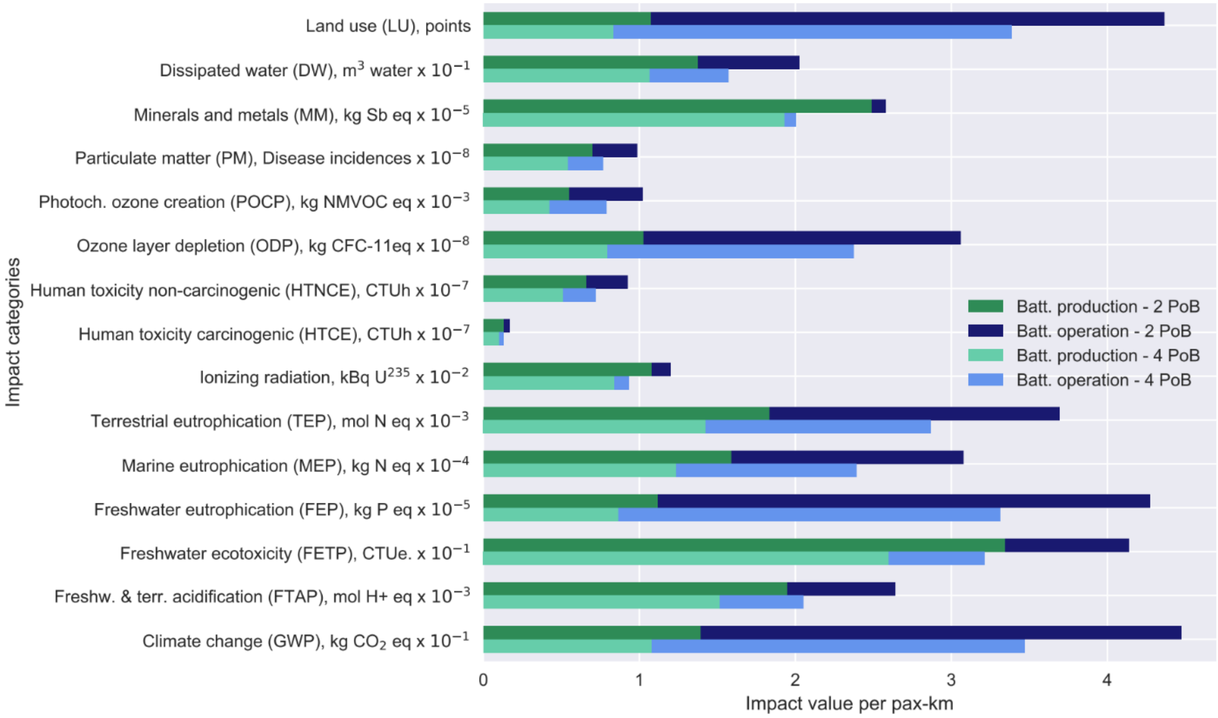

**Fig. 18 LCA of two UAM fleets with 2 persons on board vs 4 persons on board for Hamburg suburban.**

The LCA impacts of this sensitivity is shown in Fig. 18, it can be seen that due to the higher passenger capacity of the bigger vehicle (3 pax + 1 pilot) fewer flights are required and thus the impacts per passenger kilometer are smaller compared to the smaller vehicle (1 pax + 1 pilot).

### *4. What Is the Impact of Different Use Cases on the UAM Fleet and the UAM LCA?*

| Time Frame | Use Case | Vehicle | Capacity | Battery | Operations |
|---|---|---|---|---|---|
| 2025 | **California: Urban vs Suburban** | Lift + Cruise | 4 POB | NMC-811 | Piloted |

In this study the same aircraft is used for the Urban and Sub-Urban scenarios and the SoS results are presented in Fig. 19. The fleet size required to achieve 90% success percentage is 42 for both the use cases although the success percentage is higher for the Urban use case at this fleet size. For the lower fleet sizes the impact of the scenarios are larger. As expected, the energy consumption is higher for the Sub-Urban scenario as the mission ranges are longer. Despite the total energy consumption being higher for the Sub-Urban use case, the energy per pax-km is lower. This is because the cruise efficient tilt-rotor is being flown and the cruise segment is larger for the suburban use case, coupled with the normalization by distance flown to arrive at the energy per pax-km value.

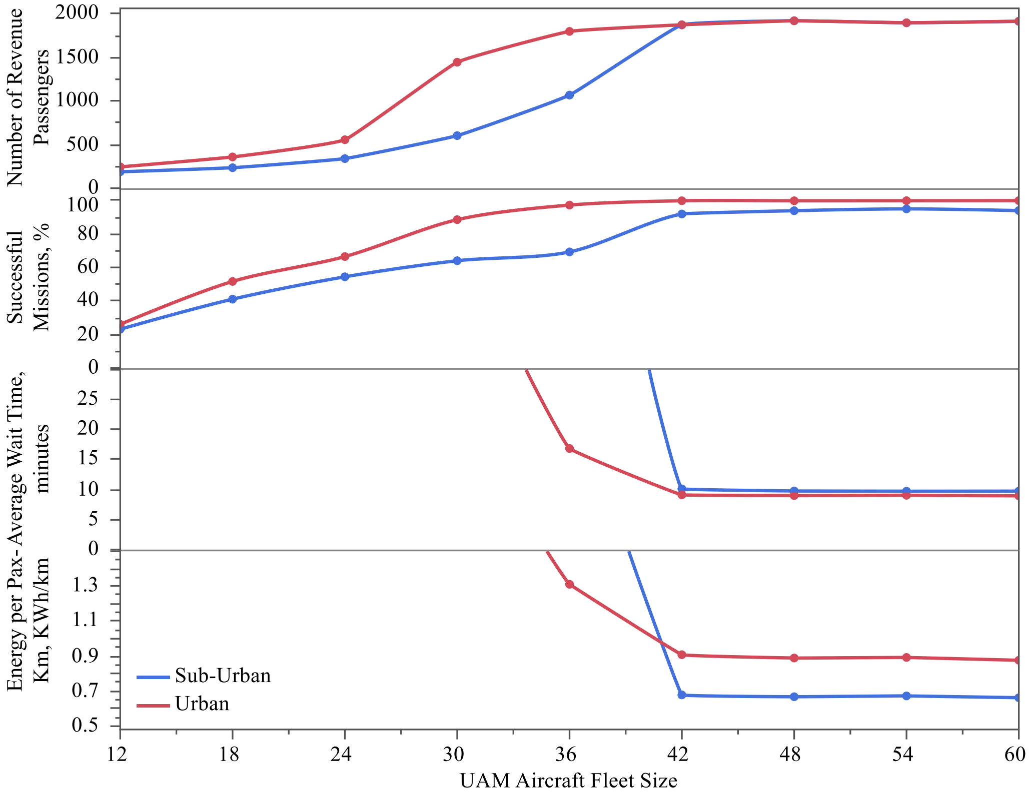

**Fig. 19 SoS comparison of the two UAM fleets in a California suburban vs urban scenario.**

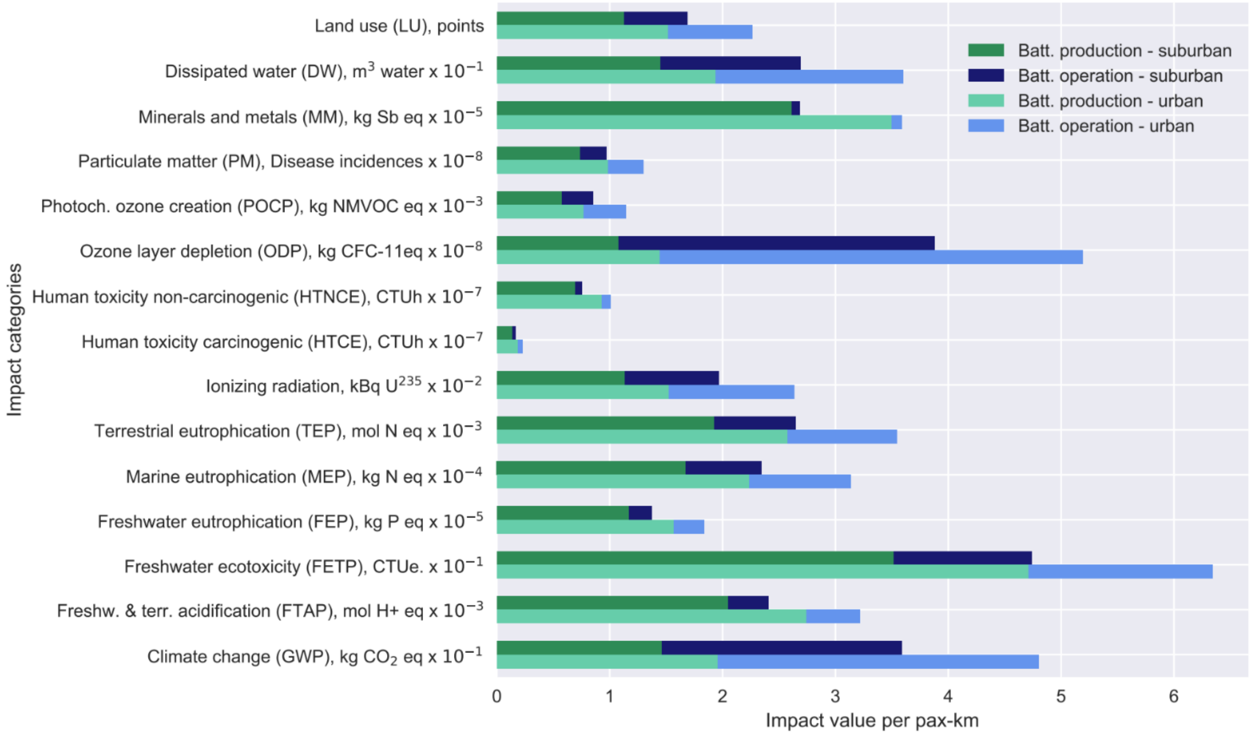

**Fig. 20 LCA of two UAM fleets in a California suburban vs urban scenario in 2025.**

When comparing the same UAM fleet in a suburban vs an urban scenario, it can be seen that the impacts of the suburban fleet are lower due to the reduced energy per pax-km as in Fig. 20.

### *5. What Is the Impact of Different Technology Time Frames on the UAM Fleet and the UAM LCA?*

| Time Frame | Use Case | Vehicle | Capacity | Battery | Operations |
|---|---|---|---|---|---|
| **2025 vs 2050** | Hamburg: Suburban | Lift + Cruise | 4 POB | NMC | Autonomous |

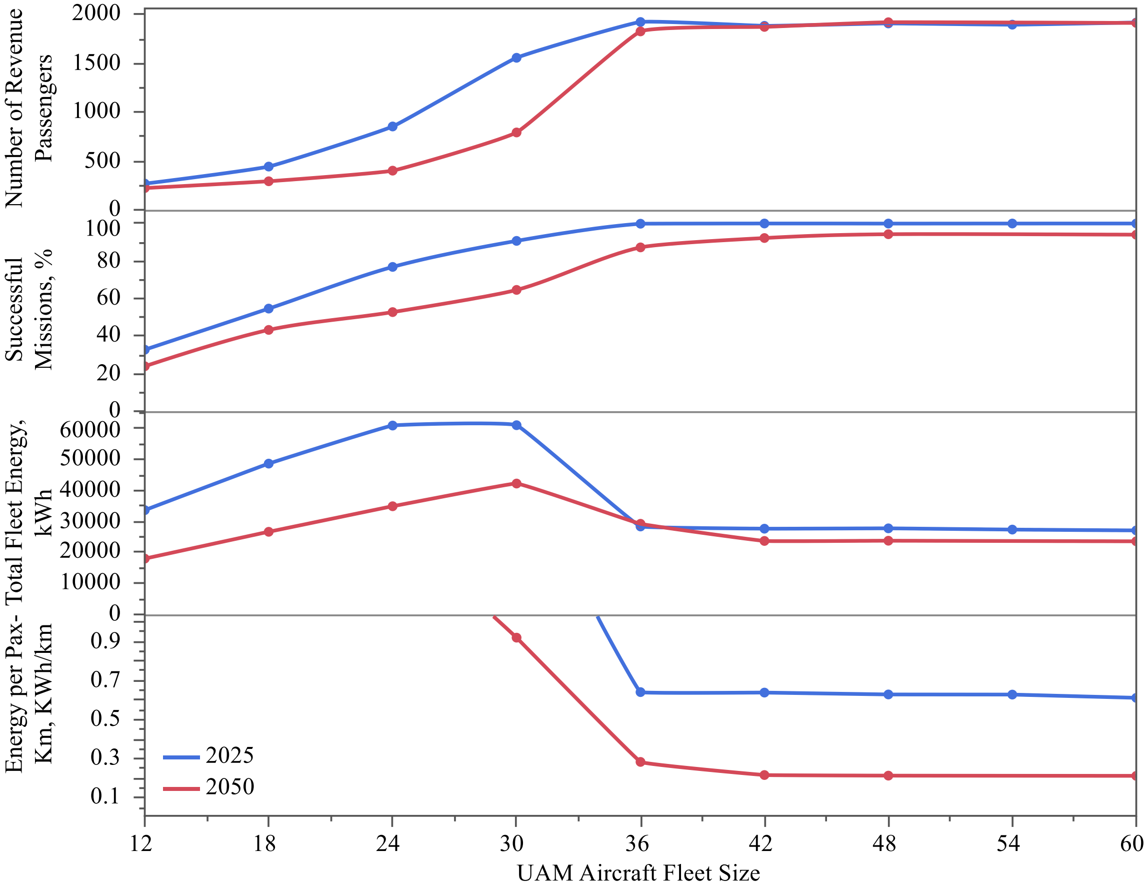

**Fig. 21 SoS comparison of the two UAM fleets in Hamburg suburban for 2025 vs 2050.**

In this sensitivity study, the technology assumptions for the energy density and the charging infrastructure for 2025 and 2050 as described in Sec II are used and the SoS results are presented in Fig. 21. It is observed that the success percentage is not significantly impacted by this variance however the total fleet energy is reduced by 50% (0.448 to 0.217 kWh/pax-km) for the 2050 scenario. This corresponds to a similarly lower energy per pax-km.

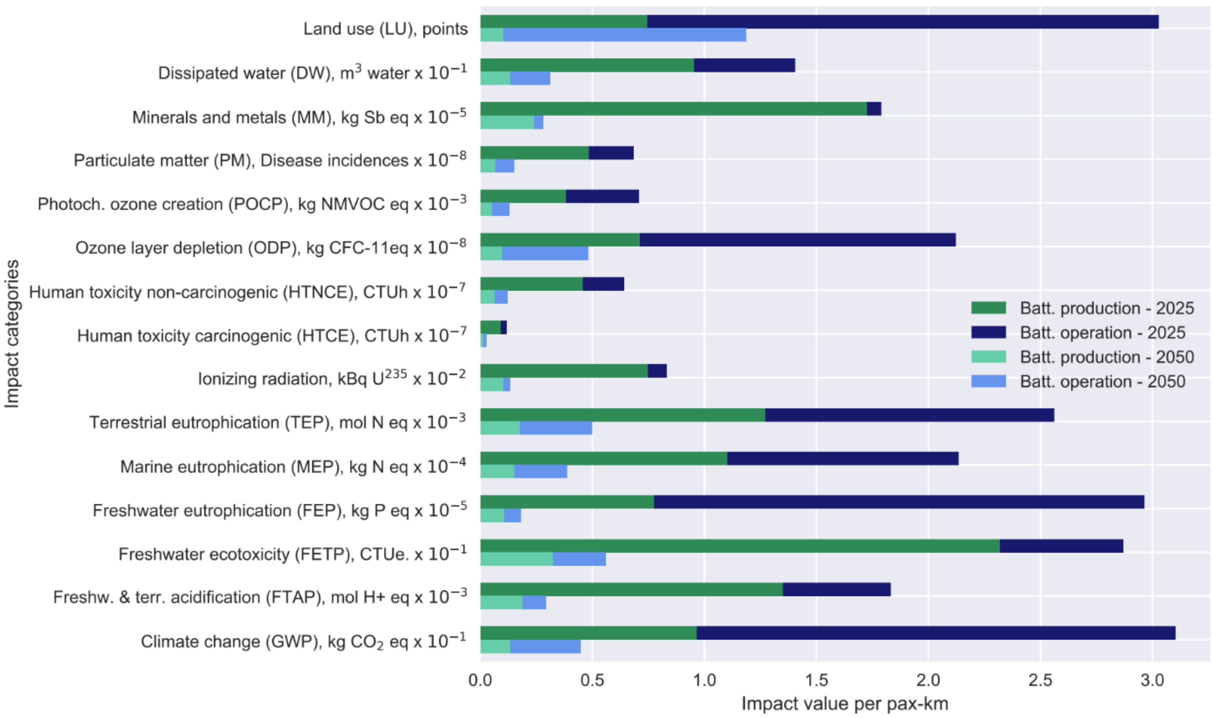

**Fig. 22 LCA of the two UAM fleets in Hamburg suburban for 2025 vs 2050.**

For the comparison of the same fleet in two different points in time (2025 and 2050) it can be seen that due to the drastic change of the electricity mix, for which the share of renewable energy rises up to 80%, the environmental impacts for the operation phase of the batteries are reduced significantly (see Fig. 22). The impact reduction of the operation phase is explained by the higher specific energy and longer lifetime (in terms of cycles) of the batteries in the 2050 scenario.

## 6. What Is the Impact of Different Battery Chemistries on the UAM Fleet and UAM LCA?

| Time Frame | Use Case | Vehicle | Capacity | Battery | Operations |
|---|---|---|---|---|---|
| 2050 | Hamburg: Suburban | Lift + Cruise | 4 POB | **NMC vs Li-S** | Autonomous |

In 2050, The impact of the battery technology is not significant on the success percentage as visible from Fig. 23. The fleet size required to achieve 90% success percentage is 36 and is the same for both fleets. However, difference in the two fleets can be seen in the total fleet energy with the fleet with Li-S batteries requiring less energy due to its higher specific energy. The energy consumed by the Li-S fleet is 0.350 kWh/pax-km compared to 0.376 kWh/pax-km for the NMC fleet.

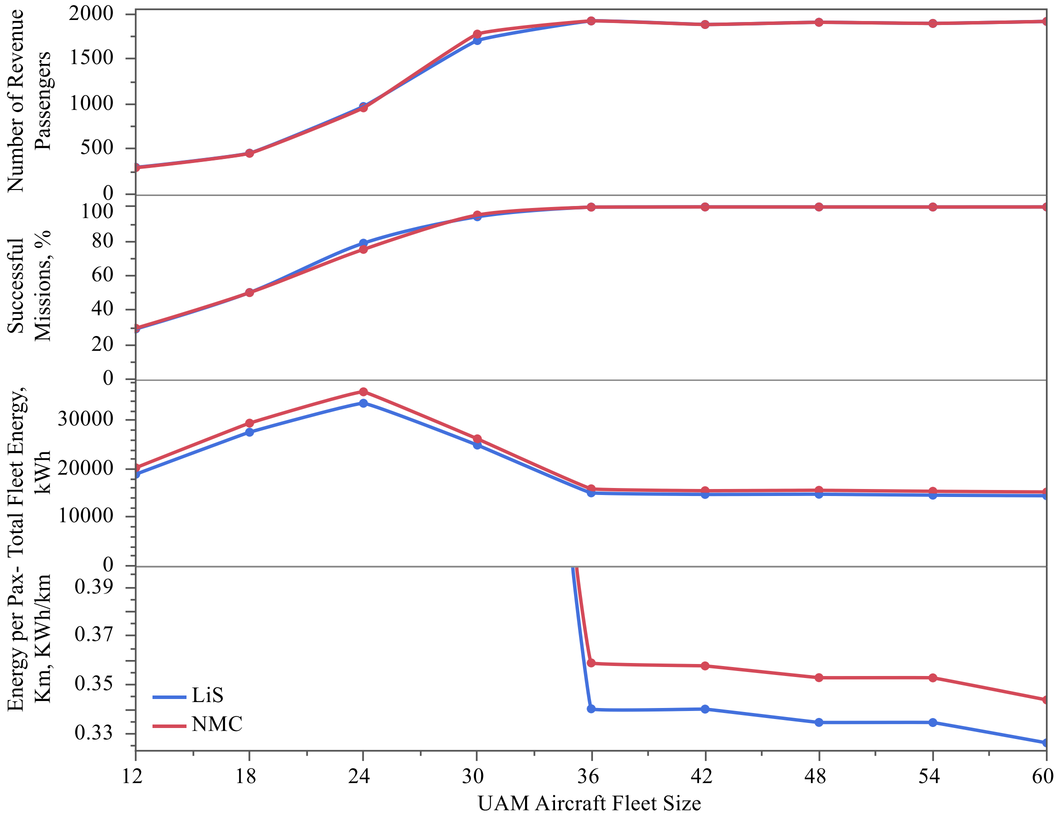

**Fig. 23 SoS comparison of the two UAM fleets using NMC batteries vs Li-S batteries in 2050.**

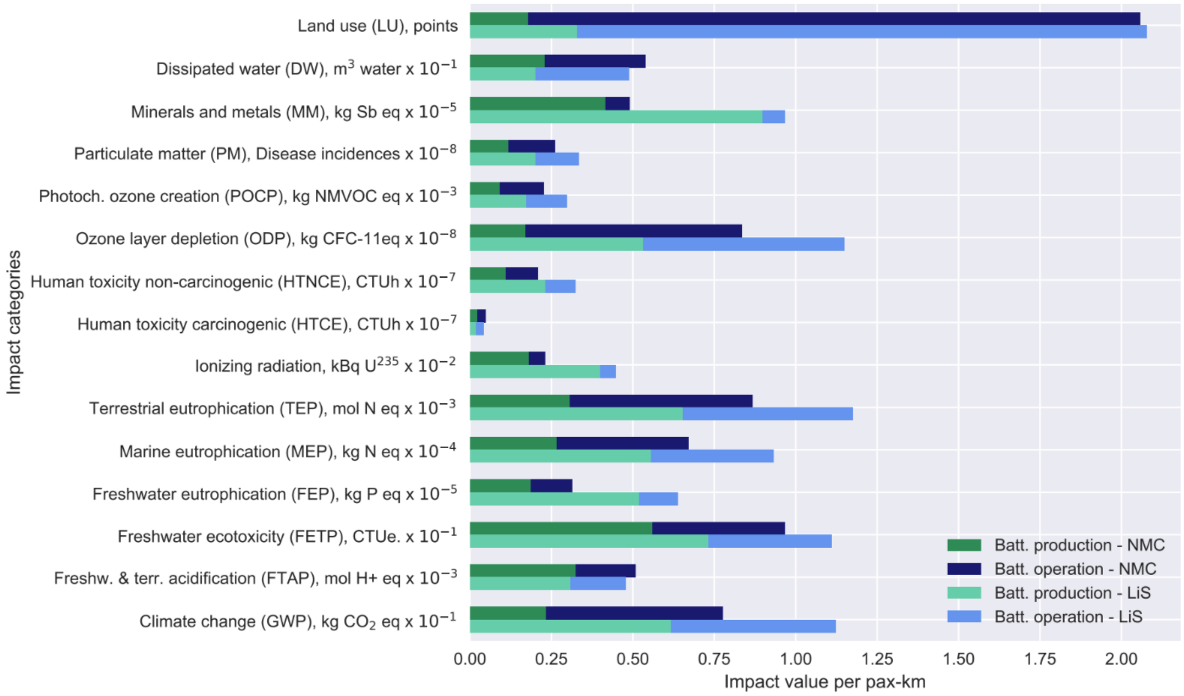

**Fig. 24 LCA of the two UAM fleets using NMC batteries vs Li-S batteries in 2050.**

The LCA results for this sensitivity study are presented in Fig. 24. Due to the higher specific energy of the Li-S batteries, the impacts of the operation phase are lower compared to the NMC batteries. However due to the lower lifetime (500 cycles for Li-S compared to 1000 cycles for NMC), the impacts of the production phase are higher for the Li-S batteries since more are needed during the lifetime of the fleet. The impacts of the battery production phase are to be viewed with caution since the inventories for the two battery chemistries come from different sources and therefore a fair comparison cannot be guaranteed. Furthermore, the inventory for the NMC chemistry is unchanged for the years 2025 and 2050 even though an increase in specific energy of this chemistry is assumed. As the changes in the composition of the battery leading to such an increased specific energy are not quantified, it was decided to use the same inventory as for the year 2025.

## V. Conclusions and Outlook

This paper has investigated the UAM case study in a System of Systems context and evaluated various sensitivities on the Life-Cycle Assessment. The SoS design space exploration and sensitivity results for approximately 450 simulation points (each point simulating 24-hour operation for different homogeneous fleets, with varied technologies and operation scenarios) have shown the complex interaction between UAM vehicle configuration effects, technology advancements, fleet operations, agent dispatching logic, and UAM throughput. It serves as a proof of concept of the holistic evaluation framework that can be developed in an SoS context by combining different fields of research. In order to ensure the concept of UAM can become a reality, it is necessary to consider its impacts as a whole by considering LCA. While in this study, assumed demands and vertiport locations were used, in the future, data-driven demand, vertiport locations, and improved vertiport operations modelling as well as aircraft trajectories can be utilized in order to then arrive at a very accurate estimate of the LCA impact of UAM operations. The CONOPS and requirements will be expanded to several more use cases and UAM framework will be expanded [27], further detailed cabin design and subsystem integration will be performed via collaborative design methods [28] – [30]. The SoS framework was used in this study for the evaluation of the impacts for given vehicle designs. It has also been used in other work to evaluate impacts of aircraft subsystem parameters on the SoS level [26], thereby moving towards the higher fidelity SoS driven design of UAM vehicles. The uncertainties of technology and design will be propagated to various levels and assessed [31] within the SoS framework in future studies.

In the context of a case study, this paper has investigated the effect of fully autonomous operations and piloted operations on the LCA in research question 1. The piloted fleet requires 75% more aircraft compared to autonomous fleet to cater same number of passengers within 15 min success criteria. Further, the investigation of the effect of different geographies on the LCA was carried out in question 2. Moreover, the effect of passenger capacity and the use case were investigated in questions 3 and 4 respectively. Research question 5 analyzed the impact on the LCA of operations in two different time frames considering the advancements of technology and methods of energy production. Lastly, the effect of two different battery chemistries (NMC and Li-S) on the LCA was investigated in question 6.

With regard to the environmental impact assessment, this work (research question 6) focused on technologies that according to literature are expected to be deployed and further developed in the future (NMC and Li-S batteries). However, further research should also consider applying the LCA methodology to compare alternative energy carriers for powering the air vehicles such as hydrogen with the implementation of fuel cell systems, which is already being considered as a feasible pathway for future more sustainable air traffic. Moreover, in order to obtain a more complete comparison between the different propulsion technologies for the UAM vehicles, an economic assessment using methods such as life cycle costing (LCC) to determine the most cost-effective scenario can be carried out. Additionally, a broader analysis considering also the manufacturing and EoL of the UAM vehicles themselves should be conducted in order to have a more complete comparison of different fleet configurations.

On the other hand, one aspect that requires further development is to define more precisely the inventories of the batteries. For instance, one approach could be to use electrochemical models that attempt to represent the expected developments in the cathode, anode and electrolyte material composition. In this way, the underlying uncertainties due to the prospective analysis can be addressed. Additionally, the end-of-life phase of the batteries including strategies for recycling, disposal or other EoL options should be modelled and evaluated for a more complete lifecycle consideration.

From an aircraft design perspective, some configurations or technologies have a detrimental effect on UAM throughput, e.g. deploying lift + cruise in urban use case. Besides the UAM network considerations, e.g. fleet size, passenger throughput, additional design criteria must be taken into consideration when it comes to the selection of a UAM vehicle configuration. Especially safety and public acceptance criteria must not be neglected.

The ability to study the impact of a single subsystem level technology parameter such as battery chemistry or passenger capacity and see its impact on the whole UAM fleet requirement and Life Cycle Assessment is not possible without this approach, several further sensitivity studies on the SoI level with its impact on the SoS level can be carried out. Furthermore, some of the outcomes are nonlinear and could not be found by analytical methods. These nonlinear effects demonstrate the need for the SoS simulation approach, as the complex interactions and snowball effects coming from SoI/aircraft or technology subsystem level changes can have unpredictable effects on the SoS level.

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