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Aircraft architecture and fleet assessment framework for urban air mobility using a system of systems approach

Prajwal Shiva Prakasha *, Nabih Naeem, Patrick Ratei, Björn Nagel

German Aerospace Center (DLR), Institute of System Architectures in Aeronautics, Hein-Saß-Weg 22, 21129, Hamburg, Germany

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ABSTRACT

This research article explores Urban Air Mobility (UAM) from a System of Systems (SoS) perspective in order to understand the impact of different fully electric UAM aircraft architectures on the overall SoS capability. For this purpose, a framework, combining aircraft design methods with an agent-based simulation, is developed. Thereby, not only different UAM aircraft architectures, but also fleet combinations, technology scenarios, and operational strategies are studied and evaluated for different success criteria. The UAM fleets are simulated for 24-hour operations, considering non-uniform passenger demand, dispatch of passenger as well as deadhead flights, aircraft architectural performance, load factor, energy consumption, and turnaround procedures. A large design of experiments, consisting of approximately 5,000 design points, is executed. Eventually, this article demonstrates the proof of concept for the proposed SoS framework and provides several parameter sensitivities for a given UAM scenario. For such complex SoS, analytical methods would not suffice for understanding complex and often nonlinear interactions. Therefore, the proposed simulation driven framework proves to be successful by providing sensitivity study results, linking subsystem, system (aircraft) and system of system (fleet) level. Thus, the framework allows for comprehensive understanding of the SoS design space and is important for successful deployment or optimization of UAM aircraft & fleet for a given city and operational context.

1. Introduction

Since the release of the Uber Elevate white paper [1] in 2016, the field of Urban Air Mobility (UAM) has gained a lot of attention from aviation research and industry. Offering a novel aerial transport system for congested urban areas, established and startup aircraft manufacturers have proposed various design concepts for the required air taxis or UAM aircraft. By the use of distributed electric propulsion, mostly fully electric Vertical Take-Off and Landing (eVTOL) aircraft have been considered for UAM operations. However, there are various eVTOL aircraft configurations or architectures among the presented concepts.

From an aircraft performance-based perspective these architectures can be characterized by their hover and cruise efficiency, which are indicated by disk loading and lift-to-drag ratio, respectively. Estimates for the design space of potential eVTOL aircraft architectures in terms of the aforementioned design variables have been provided by McDonald and German [2] and are reproduced in Fig. 1. Thus, two major groups, which are distinguished by the way lift is produced in cruise flight, can be identified. While multirotor, conventional, coaxial, and compound helicopters are classified as rotary-wing cruise architectures (see shades of red in Fig. 1), lift + cruise, tiltduct, tiltwing, and tiltrotor aircraft are categorized as fixed-wing cruise architectures (see shades of blue in Fig. 1).

Multirotor vehicles, such as the single-seat EHang 216 [3] or the two-seat VoloCity by Volocopter [4], may be more efficient in hovering flight state due to lower disk loading, but can only fulfill shorter cruise missions. Jaunt Air Mobility is developing the Jaunt Journey Air Taxi [5], a compound helicopter architecture, that may perform similar in hover, but performs more efficient in cruise flight state due to its supplementary wing. Fixed-wing cruise architectures may not be as optimal for long hover duration as the aforementioned architectures, but offer the capability of further cruise range due to higher lift-to-drag ratio, i.e. cruise efficiency. Within this group, eVTOL aircraft, such as two-seat lift + cruise Wisk Cora [6], five-seat tiltrotor Joby S4 [7], and seven-seat tiltduct Lilium Jet [8], can be found.

The term System of Systems (SoS) has been recently formalized by ISO 21839:2019 [9] 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 an approach to understand complex systems in fields such as renewable energy, national security, infrastructure,

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* Corresponding author.
E-mail address: Prajwal.Prakasha@dlr.de (P. Shiva Prakasha).

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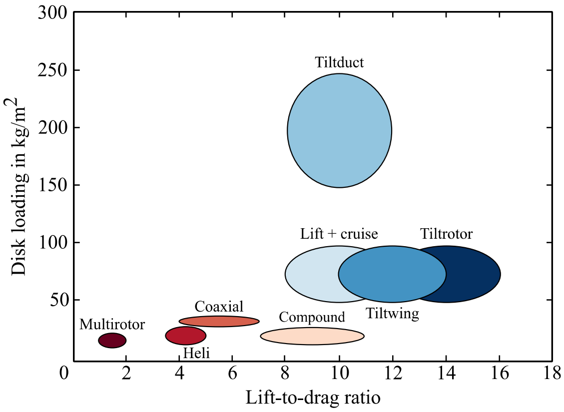


Fig. 1. Conceptual design space for different eVTOL aircraft architectures based on [2]. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

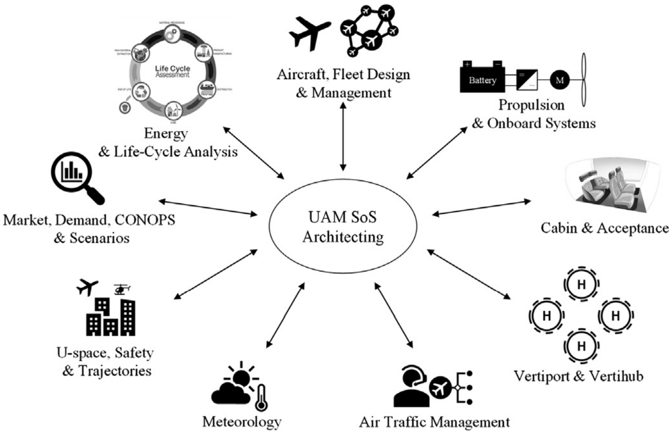


Fig. 2. Urban air mobility as a system of systems.

transport, and defense [10]. Although each field has adopted a specialized definition of SoS to suit their needs, the influential work of Maier [11] has provided a widely accepted characterization of SoS [12]. These are referred to as the Maier criteria or OMGEE characteristics [13] and are namely: Operational as well as Managerial independence, Geographic distribution, Emergence, and Evolutionary behavior.

Urban Air Mobility, as shown in Fig. 2, has constituent systems or system of interest 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 level. These systems are operationally and managerially independent. The constituent systems combined 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, meteorological or weather phenomena, etc.). The System of Interest (SoI) focused in this article is the vehicle or UAM aircraft and its associated technologies.

Previous work on UAM aircraft design has provided several comparisons of different architectures relating to overall concepts [14], mission requirements [15], cost as well as acoustics [16], and also sustainability [17]. Researchers have also shown that the concept of operations and thus the mission profile are crucial for well sized eVTOL vehicles [18]. Therefore, simulating the entire UAM network, which is considered a complex SoS, offers the possibility of studying the influences of aircraft design and performance towards the entire SoS capability. By this approach, the vehicle and subsystem level parameters can be varied to investigate their impact on the whole UAM network through the SoS level parameters such as number of passengers transported, successful missions, and energy consumption. While prior research has made use of Agent-Based Simulations (ABS) for UAM to analyze the overall transport network with regard to demand, operational performance, sensitivities [19], and cost optimization [20], only few researchers have addressed UAM aircraft performance and design aspects in the SoS context [21]. However, there has been no implementation of detailed models for parametric demand distributions and dispatching in prior UAM SoS studies.

Our research proposes a new approach to UAM aircraft design by incorporating SoS simulations in the aircraft design process in order to address SoI aspects, i.e. UAM aircraft design, in the overall context of transport network, fleet planning, and operations management. There exists a large number of “Unknown unknowns” in the operations of the UAM network ranging from the projected demand, vertiport locations, and regulations to the aircraft level parameters such as optimal architecture, velocity, and passenger capacity. In the presence of so much uncertainty, making informed decisions is difficult, therefore the authors’ approach is to empower the decision-making process through simulating the UAM network based on the available data and informed assumptions. This approach provides the designer with a wider scope of the impacts that system and subsystem level parameters would have on the overall performance of the SoS, and also allows for easy integration of new data and assumptions from the literature. Through this coupling, an optimization of the subsystems, aircraft, and fleets can be targeted based on the operational context. Moreover, the various UAM missions that will exist further compound the necessity for such an approach. While a heterogeneous fleet may ultimately be necessary to fulfill the requirements for different UAM missions, this initial study aims to demonstrate the proof of concept for the newly developed software by simulating scenarios combining UAM aircraft design and operations with regard to a homogeneous fleet. Therefore, an early case study of Hamburg in Northern Germany is conducted and analyzed considering various UAM aircraft architectures as well as two different technology assumptions.

Several sensitivity studies are carried out in this work to investigate their impacts on the UAM SoS. The parameters studied in this work are the fleet size, aircraft cruise speed, aircraft passenger capacity, aircraft sizing mission, aircraft reserve requirements (regulations), recharging technology, overall technology scenarios, and market demand variations. The understanding of these parameters is crucial for successful deployment of UAM in a given city and operational context.

2. System of systems framework

In order to assess aircraft and fleet level for UAM, a flexible and extendable SoS framework is developed (see Fig. 3). The framework is developed to enable the propagation of the subsystem and system (aircraft) level inputs to the SoS level considering the operational scenario and use case. The aircraft level inputs are the architecture, cruise speed, payload, reserve requirement, and sizing mission. Moreover, lift-to-drag ratio and disk loading can be analyzed. At the aircraft subsystems level parameters such as battery and charging technology are considered. At the SoS level, vertiport network definition, Concept of Operations (CONOPS), passenger demand, fleet size, dispatch criteria and wait time constraints are the defined inputs. The aircraft sizing with subsystems is optimized until convergence and the resulting aircraft performance is passed to the ABS where each aircraft (along with its characteristics) is modeled as an agent. The simulation is executed based on the complete definition provided at the three abstraction levels and

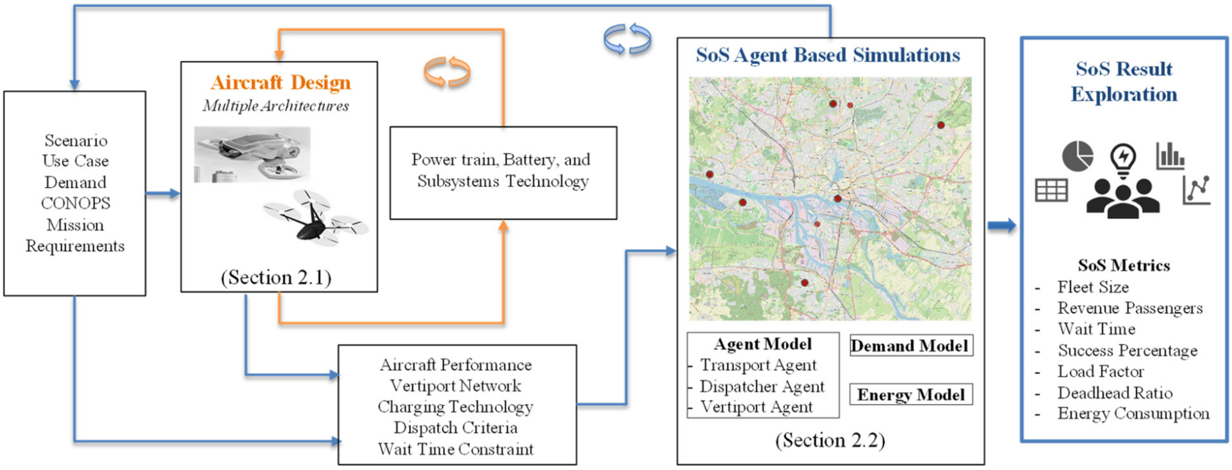


Fig. 3. System of systems framework for urban air mobility.

Table 1
Urban air mobility aircraft architecture specific assumptions based on [2] [22].

Aircraft architecture	f_{empty}	N	Hover		Cruise	
			$(T/A)_{\max}$, kg/m^2	$(\overline{C}_l)_{\max}$	V, m/s	L/D
Multirotor	0.42	8	18.3	0.6	33.3	3.5
Compound helicopter	0.5	1	21.9	0.8	67	9
Lift + cruise	0.53	8	73.2	1	67	10
Tiltrotor	0.55	12	73.2	1	67	14

the SoS performance measured through the defined SoS evaluation metrics. The UAM aircraft design tool, the ABS, and the interaction between both tools are explained in detail in the following sections. It should be noted that the feedback loop from SoS to aircraft design optimization based on SoS evaluation metrics is not carried out in this publication. This study focusses on the validation and evaluation of the framework via sensitivity studies regarding fleet/SoS, aircraft/SoI, and subsystem levels.

2.1. *Aircraft design*

The study of multiple aircraft/SoI level parameters, e.g. architecture, cruise speed, passenger capacity, and sizing mission, on the SoS level requires a rather computationally cheap tool for conceptual eVTOL design. Based on the aforementioned Top-Level Aircraft Requirements (TLAR), the tool must perform sizing and performance computations so that power requirements for different mission segments, e.g. hover and cruise, and various load factors, depending on the Persons On Board (POB), can be provided to the ABS.

Accordingly, the aircraft design process consists of initial eVTOL sizing and performance calculations, where the open source method by Brown and Harris [22] is used. Their conceptual method is referring to McDonald and German [2], thus utilizes momentum theory for hover segments and simple steady flight equations for cruise segments. Furthermore, a simple battery model, often referred to as ‘energy in a box’ model, is implemented [22].

This methodology was chosen because of its possibility to study various UAM aircraft architectures. It also allows for very short computation times. Furthermore, the methodologies for cost estimation as well as noise assessment may be used in future work.

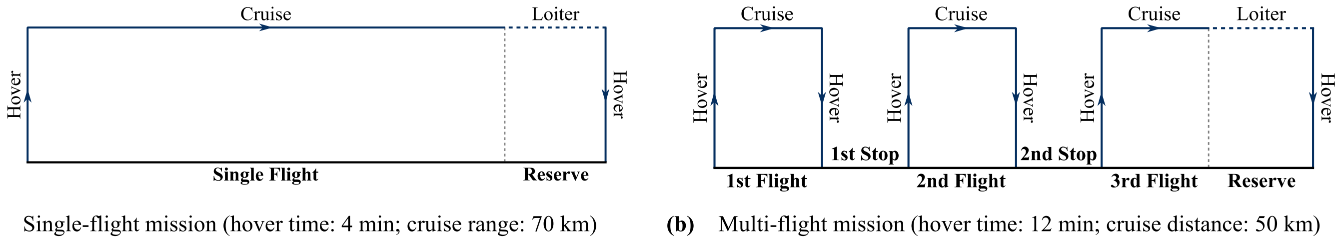
The architecture specific assumptions for constant empty mass fraction f_{empty}, number of rotors N, and cruise as well as hover parameters, i.e. typical cruise speed V and corresponding lift-to drag ratio L/D as well as maximum values for disk loading $(T/A)_{\max}$ and rotor mean lift coefficient $(\overline{C}_l)_{\max}$, are summarized in Table 1. While the assumptions generally follow [2][22], as previously depicted in Fig. 1, the cruise assumptions of the multirotor architecture are estimated more optimistically in reference to the sizing results of the quadrotor concept presented by Silva et al. [23].

Table 2
Technology assumptions for two different scenarios.

Parameter	Scenario	
	Near-term	Far-term
Battery specific energy, Wh/kg	300	500
Battery specific power, W/kg	3,000	5,000
Charging power, kW	250	1,000
Useable energy fraction	0.8	0.9
Autonomous operations	Only deadhead missions	All missions
Reserve requirement	20-min loiter	5-nmi diversion

Apart from architecture specific characteristics, overall technology assumptions are set up and shown Table 2. Here, two different scenarios – near-term and far-term – are considered. In terms of battery energy, note that the battery specific energy is assumed for the pack level. Charging power is not considered in the context of UAM aircraft sizing, but will be used in the ABS. In order to extend battery life, a factor that considers the useable battery energy is introduced, so that operation at low and high state-of-charge is inhibited. While the near-term assumptions are somewhat optimistic regarding battery technology, the far-term scenario assumes a very drastically improved technology level. Furthermore, the UAM operation is expected to be fully autonomous or remote-piloted in the far future, while autonomous deadhead (empty) flights may already be possible in the near future. The requirement for reserve energy is assumed to transition from a time-bound loiter segment into a distance-related diversion segment. Initially, a 20-minute loiter, which is taken from rotorcraft requirements, is considered. The assumed diversion requirement for advanced UAM operations only accounts for a reserve of 5 nautical miles (nmi) or approximately 9.3 km at cruising flight conditions. Overall, very optimistic and design favoring assumptions are set up in the far-term scenario.

In this study, two different sizing missions are considered, which result in divergent sizing results depending on the UAM air-



(a) Single-flight mission (hover time: 4 min; cruise range: 70 km) **(b)** Multi-flight mission (hover time: 12 min; cruise distance: 50 km)

Fig. 4. Urban air mobility aircraft sizing missions.

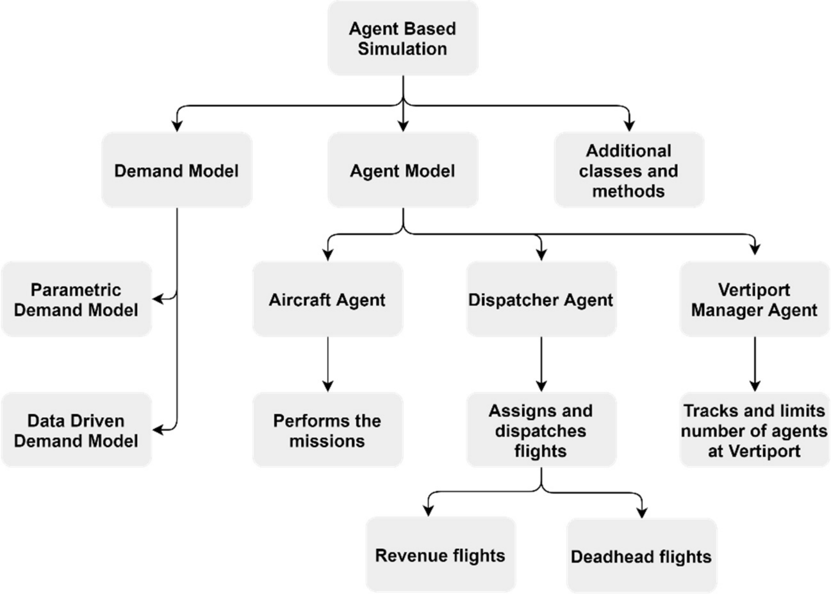


Fig. 5. Urban air mobility agent-based simulation approach.

craft architecture. For the single flight mission with a range of 70 km, a fixed-wing cruise architecture may be beneficial, whereas the multi-flight mission with a total range of 50 km contains six hover segments, and therefore, rotary-wing cruise architectures may perform better. The vertical take-off and landing segments are represented by hover out of ground effect at standard sea-level conditions for a duration of 2 minutes each. The two sizing missions are shown in Fig. 4 (a) and Fig. 4 (b), respectively.

Regarding the sizing results, the tilt duct architecture is not concerned at all, as the given methodology does not represent it well [22]. Furthermore, UAM aircraft with a Maximum Take-Off Mass (MTOM) greater than 3175 kg are not taken into consideration as per VTOL certification requirements by EASA [24]. Finally, the aircraft performance is computed for all possible mission segments and load factors. Here, the power required is a constant value for each segment. Also note that the pilot occupies a passenger seat in the near-term scenario.

2.2. Agent-based simulation

This section explains the DLR in-house ABS for analyzing a complex SoS. The developed ABS framework is extended for the UAM use case. The ABS for UAM is composed of two main models (see Fig. 5), the demand model and the agent model with additional methods and classes defined for implementation of the desired features. Firstly, the simulation capabilities are explained, following which the implementation of the main models are described. The simulation framework was developed with an emphasis on modularity. As such, the capabilities to simulate any desired city, region or country with ease are incorporated. The procedure for setting up a UAM use case consists of the definition of four components, namely: region of interest, infrastructure systems, demand, and fleet.

The definition of the region of interest can be done by either the region name or the GPS coordinates of the bounding box. In both cases, simply defining these inputs allows for the automatic retrieval of the map of the region of interest.

The infrastructure systems, namely the vertiports can be defined through user input of its locations or through the automatic retrieval of specific location types such as subway stations or airports.

The definition of demand and fleet will be considered in Sections 2.2.1 and 2.2.2, respectively.

2.2.1. Demand model

In the ensuing discussion, the term ‘demand’ is used synonymously with passenger. 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 demand model, special care was given to ensure it is modular to allow for quick modification of the demand model based on the available data. The demand model consists of inflow and outflow demand curves defined at each vertiport. The outflow demand curve governs the demand for outgoing trips from a vertiport. Conversely, the inflow demand curve governs the demand for incoming trips to a vertiport. The definition of the inflow and outflow curves is as depicted in Fig. 6. The demand curves are defined by a combination of multiple normal curves constituting the desired demand distribution. Each individ-

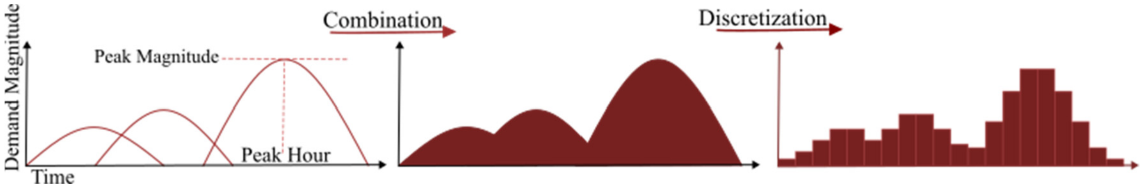


Fig. 6. Definition of the demand curves.

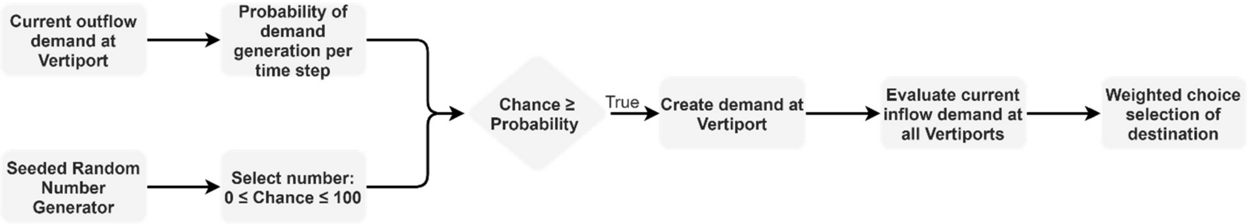


Fig. 7. Demand generation logic.

ual normal curve is 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 demand curve descriptions are then discretized into hour-long segments with their respective demand magnitudes evaluated at the middle of the hour-long segment. This way of modelling the demand allows the rapid modification of the overall demand through changing the inputs to inflow and outflow curves at each vertiport.

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 between 0 and 100. If the chance value is greater than the probability, an outgoing 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. This means that the higher the inflow demand magnitude at a vertiport at the given time, the more likely that it will be chosen as the destination. From this point, the agent model is tasked with the assignment and dispatching of agents to fulfill the mission. In summation, the outflow demand curves are used for the generation of the demand at a vertiport whereas the inflow demand curves are used for the assignment of the destination of the generated demand.

This work provides a proof of concept of the SoS driven aircraft design framework by investigating the impact of the aircraft design variables for an assumed demand model. As the demand for UAM operations is not well known in literature, the demand inputs used in this study are informed assumptions. In the future work, data driven demand will be incorporated in the investigations, as soon as it becomes available.

2.2.2. Agent model

The agent model consists of the aircraft agents, the dispatcher agent, and the vertiport manager agents. The fleet definition consists of defining the number and characteristics of the aircraft agents. The cruise speed, passenger capacity, and technology assumptions 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 homogeneous 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 in a first come first serve basis, 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 competition of the new demand, the agent considers the time needed to complete the active mission, if any, and any required charging time. The charging time is computed based on the estimated energy required to complete the new revenue mission and accounting for the energy required to complete the active mission. The parameters considered in the bidding model normalized by the time taken to fly the furthest distance between any two vertiports, the maximum passenger capacity, and the total battery capacity respectively. The bid equation is as follows:

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

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

The weightage factors (w_1, w_2, and w_3) in the bidding model are selected to reflect the chosen dispatching priorities: maximizing load factor, minimizing wait time, and the prioritization of higher charge states. These factors establish a hierarchy of priority as the weightage factors are set with an order of magnitude difference to ensure each additional level of priority is impactful only in the case of a tie in the higher levels of priority. 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 which the mission was assigned is not in the same vertiport as the demand, in such a

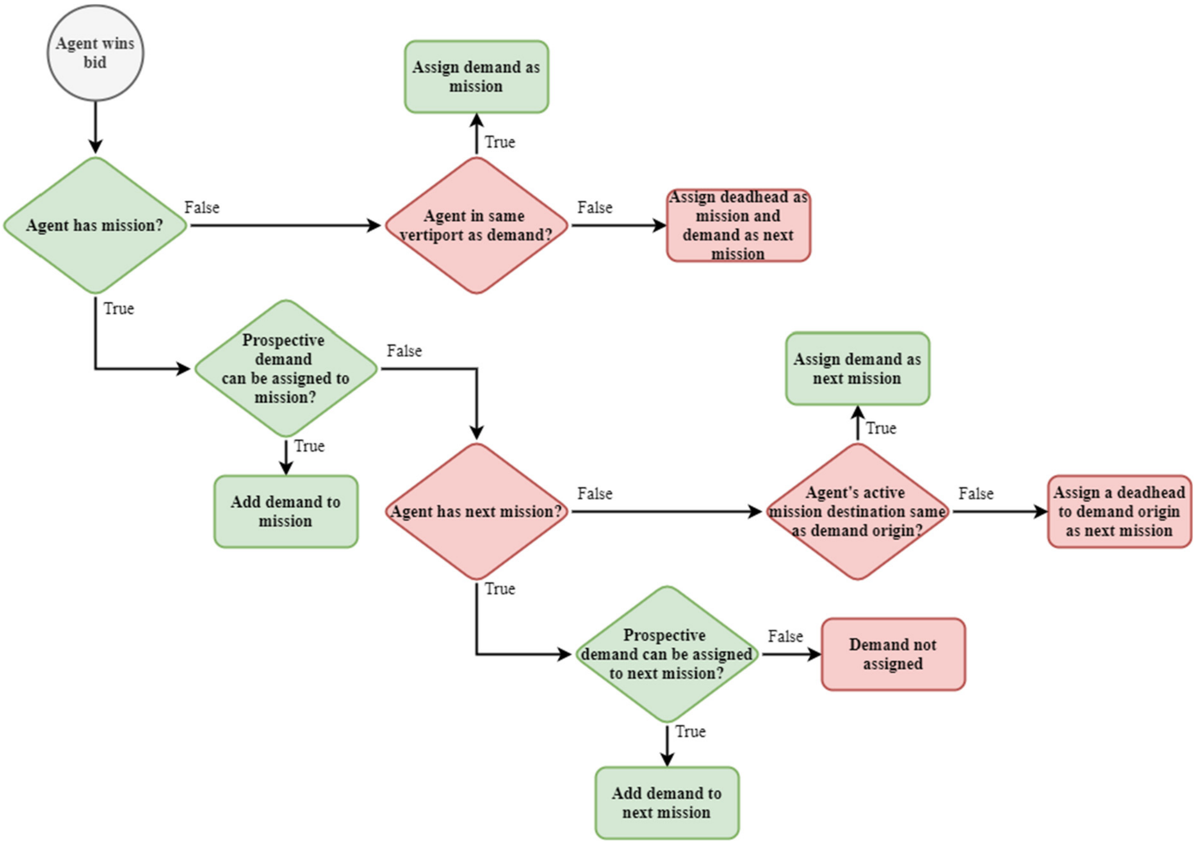


Fig. 8. Logic for demand allocation to aircraft agent.

case a deadhead demand is dispatched to transport the agent to the required vertiport. Deadhead flights are necessary to alleviate network imbalance by the redistribution of the aircraft from vertiports with low passenger demand to vertiports with high passenger demand [25].

Once the mission is assigned, the aircraft awaits dispatch by the dispatcher. If the assigned mission of the aircraft agent is a revenue mission, then the aircraft agent is dispatched when the dispatch criteria are satisfied. The dispatch criteria to satisfy are 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 next mission. It is possible that prior to the dispatching of the deadhead mission, a demand can be assigned to this deadhead mission given that they are flying from and to the same vertiports. This means that, in rare cases, there can be passengers on a flight initially scheduled as a deadhead flight.

The vertiport manager agent has two objectives: assigning hold positions as well as providing takeoff and landing clearance to the agents. The agents await landing clearance in the assigned holding positions before they land at the vertiport. Lastly, the vertiport manager also limits the number of aircraft at a vertiport to the user defined max capacity, although this limitation is not used in this study.

2.2.3. Energy model

The energy model in the simulation is tasked with tracking and updating the energy consumption and recharging. In the sizing tool, the power consumptions for the revenue, and deadhead missions are computed. The power consumptions of the revenue mission are computed for each possible load factor. Moreover, the power consumed at each state of flight of the simplified mission profile, namely hover and cruise states, is made available to the simulation. 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 90% is considered. All aircraft agents are assumed to start the simulation with a fully charged battery, more specifically each agent has the energy of the maximum battery energy capacity reduced by the usable energy fraction and the energy required to fly the reserve mission. In addition, it is worthy to note that, in the simulation, for the revenue mission the hover requirement is 90 seconds for take-off and landing, whereas in the sizing mission the hover requirement is 2 minutes (see Fig. 4). In the case that the vertiport is fully occupied, an additional 30 seconds of hover flight is mandated. However, in this study the vertiport capacity is not limited and this consideration is left for future work. Lastly, as the considerations in this study are at the conceptual aircraft design level, simplifying assumptions are taken as stated and as such the exact data should be taken with care.

2.3. Connection of aircraft design and agent-based simulation

The aircraft design tool and the ABS are connected through the transfer of input and output files. This workflow has previously been described in Fig. 3. Initially, a Design of Experiments (DoE) is set up with all the input parameters. Each design point in the DoE is sized for each aircraft architecture in consideration. Then the aircraft design tool outputs an extended DoE with the addi-

Table 3
Inputs for the design of experiments.

Parameter	Count	Specific design points
Scenario	2	Near-term, far-term
Sizing mission	2	Single-flight, multi-flight
Aircraft architecture	4	Multirotor, compound helicopter, lift + cruise, tiltrotor
Cruise speed, m/s	3	25, 40, 55 (extrapolated based on Table 1; see Section 2.4)
Passenger capacity	2	2, 4
Charging power, kW	3	250, 500, 1000
Passenger demand	2	Low (a max of 24 per hour), high (a max of 48 per hour)
Fleet size	9	12, 18, 24, 30, 36, 42, 48, 54, 60
Vertiport capacity	1	100 (unlimited; see Section 2.4)

tional performance and aircraft parameters for each viable aircraft architecture along with the necessary inputs to setup the simulation. Subsequently, the DoE runner module of the ABS executes the DoE with multi-processing and outputs the results. The inputs to the conducted DoE are summarized in Table 3.

2.4. *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. 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. The 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 are simple direct flights consisting of only hover and cruise segments, as shown in the mission profile (see Fig. 4). Ideally, the trajectories should be modeled more complex and, therefore, closer to what is expected in reality. More detailed work will be carried out as explained in the dedicated paragraph on future work (see Section 4.8).
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, empty weight fraction. Especially the variation of cruise speed within the presented framework must be taken with care as other given characteristics, e.g. lift-to-drag ratio, remain constant. This means that the given aircraft architectures may not always be precisely replicated with regard to their real-world counterpart, but rather the defined aircraft characteristics are used for sizing and simulation. Thus, future work will focus on a more sophisticated modelling of aerodynamics and weights with respect to different UAM aircraft architectures.

3. Case study for the validation of the SoS framework

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 defined parametrically based on the transport trends at the vertiport locations. With regards to future work, this assumed data will be replaced by projected demand data for UAM operations as the research is made available. Moreover, the vertiport locations should be derived based on the city topography, demand, and intermodal transport. The vertiport locations are *assumed* for this current study, but can be easily varied using latitude and longitude coordinates.

This case study considers the city of Hamburg in Northern Germany as an example. It should be noted that Hamburg is one of the most traffic congested cities in Germany and is one of the model cities for UAM adoption. The river flowing through the city may help early adoption considering safety. Further on, Fig. 9 shows the demand distribution at six vertiports for the city of Hamburg, demand and vertiport locations *assumed*. The average distance between the vertiports is approximately 15 km.

The DoE variables are summarized in Table 3, below. In terms of cruise speed, it should be noted that the aircraft performance characteristics are extrapolated based on the values, which were initially presented in Table 1. This means that only the cruise speed, but not the corresponding lift-to-drag ratio is changed for sizing and simulation (see limitations in Section 2.4).

Approximately 5,000 design points were simulated in this DoE and particular trends are presented and discussed in the following. It is important to note that the seed provided to the seeded random number generator is kept constant for each DoE run. Thus, it is ensured that each run has the exact same generation of demand (see Section 2.2.1).

Additionally, in order to examine the robustness of the framework, a trial study regarding a different city, Moscow in Russia, was also performed. Here, the average cruise distance is 30 km. The results are not presented in this publication, but will be made available in a future publication.

4. Results and discussion

The results provide observations made during this SoS driven UAM aircraft design exploration. As shown in Fig. 10, several Multi-level sensitivity studies regarding fleet/SoS, aircraft/System/System of Interest, and subsystem level are provided and discussed in the following sections. Each sensitivity study emphasizes the need for analyzing UAM from a SoS perspective, while checking for robustness of framework. Consequently, the sensitivity of several input parameters and their impact on the UAM SoS performance is studied:

1. Cruise speed
2. Passenger capacity
3. Sizing mission
4. Reserve requirement
5. Charging technology
6. Technology scenario
7. Passenger demand

The success criterion 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 is considered 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

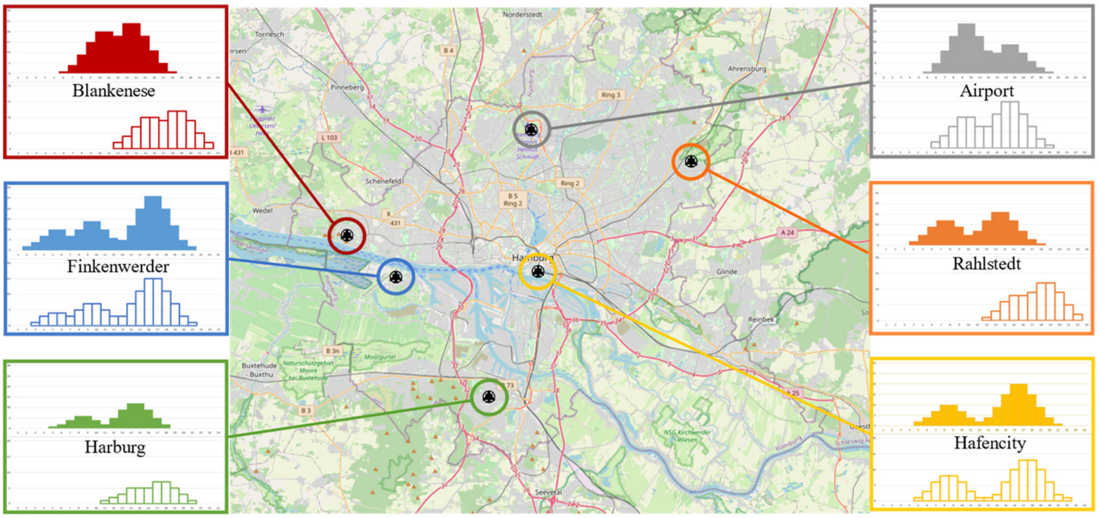


Fig. 9. Exemplary urban air mobility use case for Hamburg, Germany showing assumed vertiport locations and their assumed demand distributions (outflow in solid color, inflow with no fill).

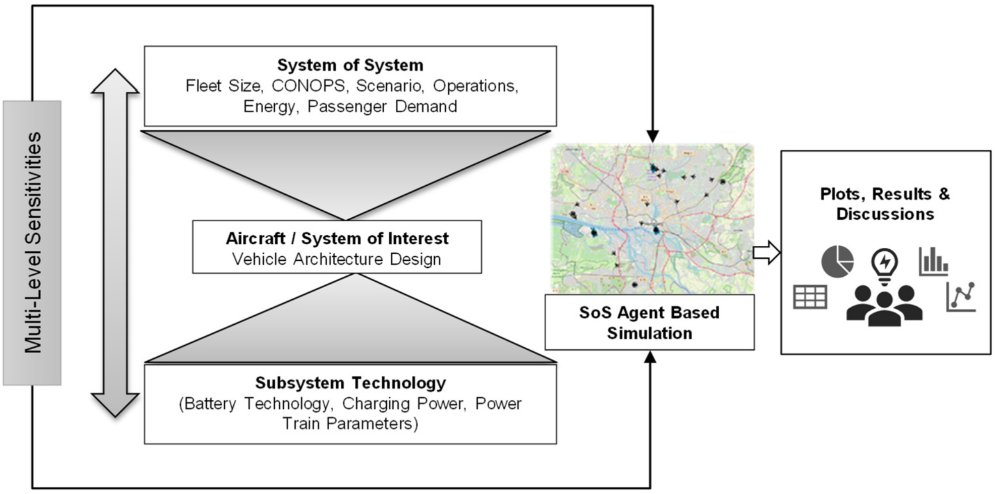


Fig. 10. Multi-level sensitivity studies and discussions.

as the primary factor for gauging the success of the SoS, and is hereby referred to as the success percentage. All evaluation parameters shown in the results of this study are explained in the following:

- Revenue passengers [count] – Total number of passengers transported
- Wait time [min] – Elapsed time from demand creation in the simulation until take-off
- Average wait time [min] – Average wait time of all revenue passengers
- Success percentage [%] – Percentage of revenue passengers waiting less than the target wait time of 15 min
- Deadhead ratio [non-dimensional] – Ratio of deadhead flights (non-passenger carrying flights)
- Load factor [non-dimensional] – Average load factor of all revenue and deadhead flights (computed excluding the pilot)
- Fleet energy [kWh] – Total energy used by the UAM network or UAM SoS fleet
- Energy per kilometer [kWh/km] – Energy used by network divided by the total distance travelled within the network
- Energy per passenger-kilometer [kWh/km] – Energy used by the aircraft per kilometer accounting for the load factor

4.1. Sensitivity of cruise speed

Cruise speed	POB	Sizing mission	Passenger demand	Technology scenario
25 vs 40 vs 55 m/s	4	Multi	High	Near-term

By varying the cruise speed of the aircraft in the fleet, a wide range of viable fleet and aircraft architecture are observed from Fig. 11. As expected, a fleet with a higher cruise speed performs better in terms of success percentage. Considering the success percentage at a fleet size of 60 aircraft, increasing the speed from 25 to 55 m/s results in an increase in success percentage of approximately 6% (shown by annotations A & B). This effect is even larger for fleet sizes that are on the border of being able to serve the existing passenger demand. The ability of the fleet to serve the demand can be seen clearly from the revenue passengers, as fleet size is increased the revenue passengers also increase up to a point after which it flatlines marked by annotation CD and DE respectively. The fleet sizes for which the revenue passengers' curve has flatlined (annotation DE) are the fleets able to serve the demand, fleets with fewer agents are unable to serve all the demand (annotation CD). Considering a fleet size of 30, the speed increase from 25 to 55 m/s corresponds to a doubling of the success percentage shown by annotations F & G. Moreover, the faster fleet require less deadhead flights at the lower fleet sizes (demonstrated by annotations H, I & J). At the larger fleet sizes, the cruise speed impact on deadhead ratio is negligible as there exists surplus agents than required to serve the demand. The main behavior observed is that the same SoS performance can be reached either through a larger yet slower fleet or smaller yet faster fleet. For a similar passenger transporting capability, decreasing the speed from 55 m/s to 25 m/s (a reduction of about 55%) necessitates an increase of fleet size from 24 to 30 aircraft (an increase of 25%). Considering the SoI level parameters, the MTOM of the aircraft increase as the speed is increased. For a near term scenario and 4 persons on board, the multirotor concept only converges to a weight below 3175 kg for the cruise speed of 25 m/s. Furthermore, as the weight increases with the sizing cruise speed, at a speed of 55 m/s, the lift + cruise concept is also unable to meet the weight requirement. As expected, the energy per km tends higher with the cruise speed (annotations KL). This shows the tradeoff of increasing the cruise speed, although the SoS performance increases with the speed, the energy per km and subsequently the total network energy increases as well resulting in a costlier fleet to operate. Additional considerations such as noise, sustainability, and life-cycle cost can aid in the decision between different viable fleets.

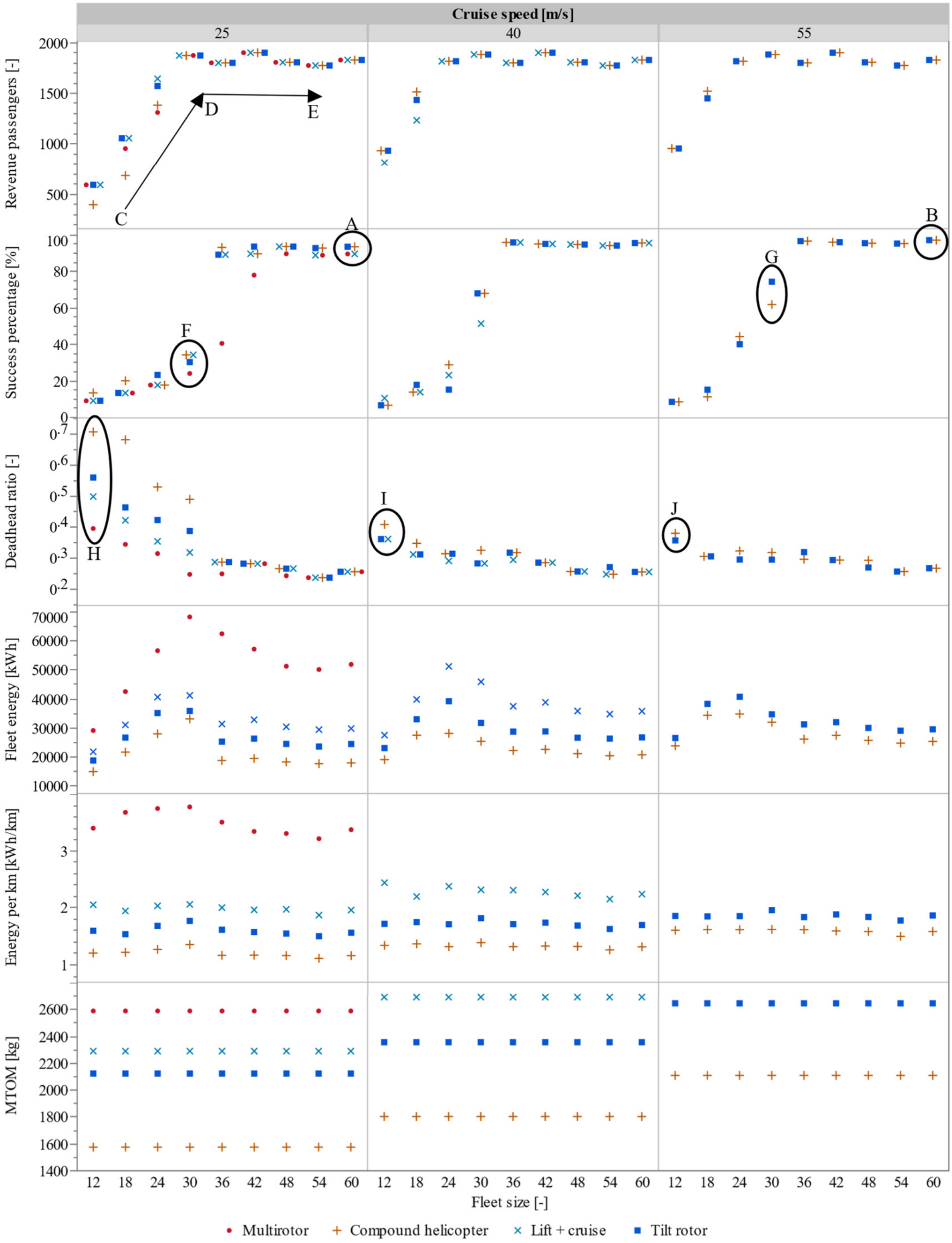


Fig. 11. Sensitivity of aircraft cruise speed.

4.2. Sensitivity of passenger capacity

Cruise speed	POB	Sizing mission	Passenger demand	Technology scenario
40 m/s	*2 vs 4*	Multi	High	Near-term

By varying the passenger capacity of the aircraft, we can investigate the sensitivities of this parameter and its impact on the entire SoS (see Fig. 12). In the near-term case, a person onboard capacity of 2 and 4 is investigated which corresponds to a revenue passenger capacity of 1 and 3 respectively (accounting for the pilot). For a fleet consisting of aircraft flying at 40 m/s with capacity for one revenue passenger, the fleet becomes viable (considering success percentage above 80%) at 54 aircraft for some architectures (annotations A, B & C). However, for a fleet consisting of aircraft with capacity for three revenue passengers, the required fleet size reduces to 36 aircraft (shown by annotation D, E & F). Thus, by doubling the Persons on Board (POB) of the aircraft, the required fleet size drops by 33%. Accounting for the seat occupied by the pilot, the doubling of the POB corresponds to a tripling of the revenue passenger carrying capacity. In terms of just being able to serve the existing demand regardless of the success percentage, a fleet of 54 aircraft is required for 2 POB fleet whereas by doubling the POB, a reduction of 55% (fleet size of 24 aircraft) in the required fleet size is possible. In fact, for any fleet

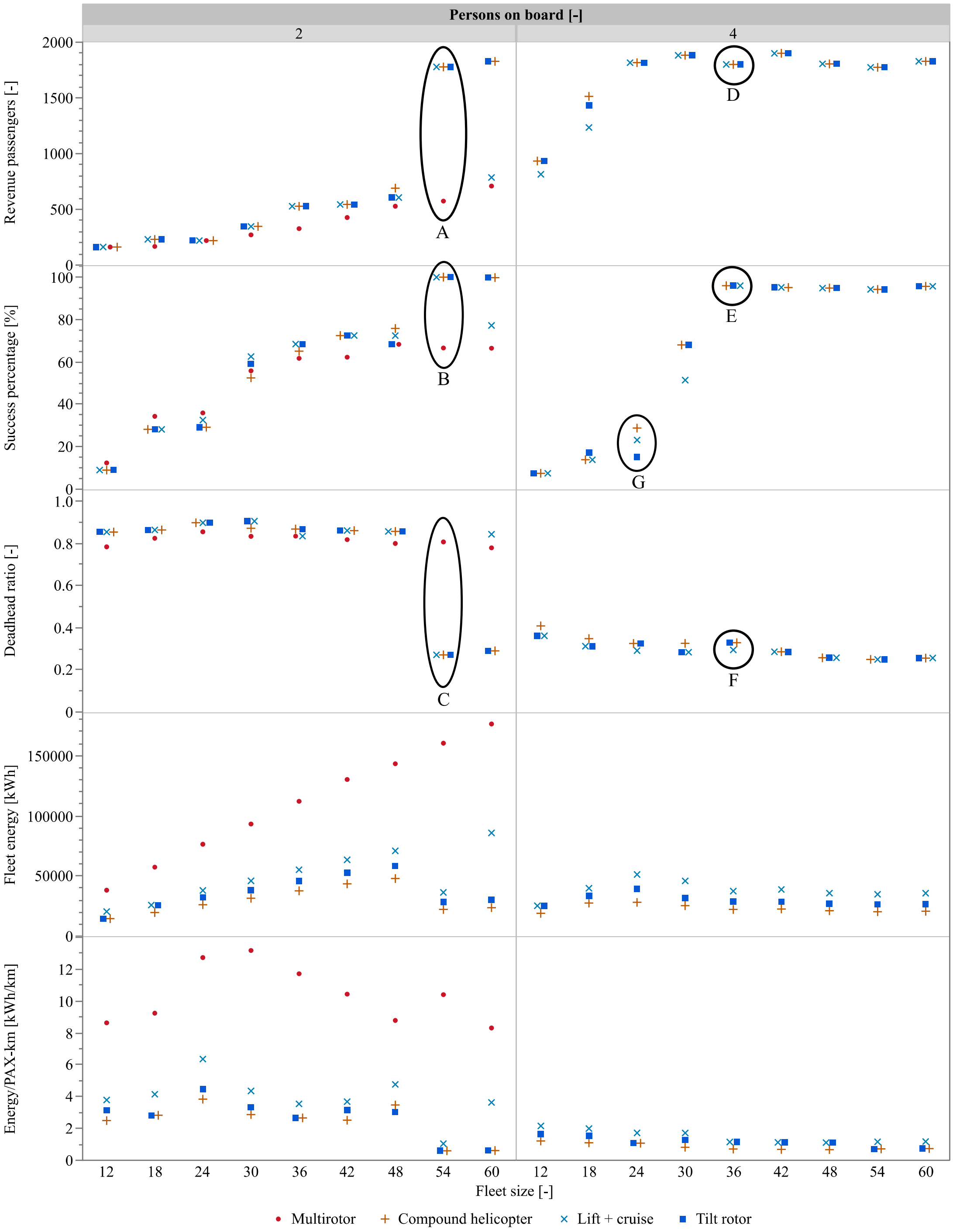


Fig. 12. Sensitivity of aircraft passenger capacity.

size the larger passenger carrying capacity outperforms the lower passenger carrying capacity fleet in terms of the Measures of Effectiveness (MoE) for this demand/market scenario. Moreover, for the higher passenger carrying capacity fleet the required deadhead ratio is significantly lower for majority of fleet sizes. The energy used by the network is observed not to increase with fleet size of 24 and greater for the 4-passenger capacity fleet as the demand is able to be met with this fleet size (although unsuccessfully in terms of success ratio, shown by annotation G). The improved efficiency of the 4-passenger capacity fleet is more clearly demonstrated by the energy per passenger km values, which regardless of fleet size are lower when compared to the 2-passenger capacity fleet.

4.3. Sensitivity of sizing mission

Cruise speed	POB	Sizing mission	Passenger demand	Technology scenario
40 m/s	4	*Multi vs single*	High	Near-term

The effect of sizing on the SoS performance is investigated through the sizing of single-flight and multi-flight missions and the results are shown in Fig. 13. The mission profiles for both sizing missions are given in Fig. 4. The sizing mission impact appears not to have a general effect across different architectures. The lift +

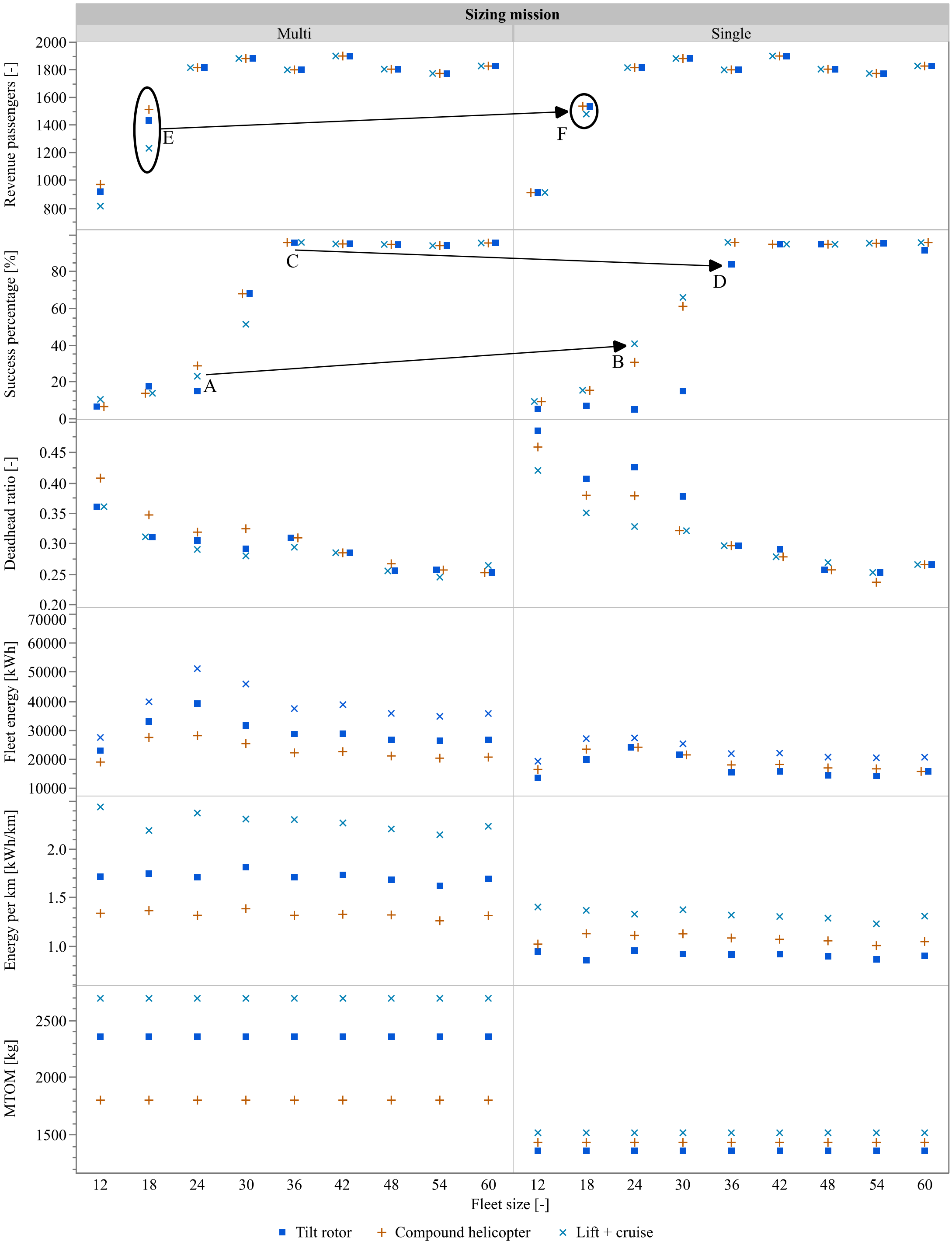


Fig. 13. Sensitivity of the aircraft sizing mission.

cruise fleet performs better with the single sizing mission than with the multi sizing mission across the different fleet sizes with an improvement of 17% in the success percentage at a fleet size of 24 as shown by annotation AB. The compound helicopter fleet performs similarly for both the sizing missions, however, counterintuitively, the cruise-performant tilt-rotor fleet performs worse with the more cruise intensive single-flight sizing than with the hover-intensive multi-flight sizing mission (shown by annotation CD). Approaching the sizing mission impact from a network energy aspect, for a similar SoS performance in terms of success percentage and deadhead ratio (for fleet sizes of 42 and higher), the energy used by the 'single-flight sized' aircraft UAM network is 20-45% (depending on architecture) of the 'multi-flight sized' aircraft UAM network with same fleet size. Lastly, the single sizing mission proves to be more capable in terms of the number of passengers served for all architectures (denoted by annotations EF), although the success percentage is lower only for the tiltrotor concept (annotations CD).

In terms of the SoI/System/aircraft level parameters, the MTOM of all the architectures are significantly lower for the single-flight sizing mission than with the multi-flight sizing mission. It is worth noting that with these use-case settings, the multirotor concept converges to a MTOM higher than 3175 kg and thus cannot be classified under EASA SC-VTOL. For this reason, the multirotor is filtered out. It is worth note that the ranges of the two sizing missions considered in this study are larger than would typically be flown by a multirotor aircraft, reducing the sizing range may result in improvements in the performance of the multirotor architecture. Considering the energy efficiency of the fleets, the fleet utilizing the least energy per km varies depending on sizing mission. The tiltrotor fleet consumes the least amount of energy, with the single-flight sizing whereas the compound helicopter consumes the least amount of energy with the multi-flight sizing mission. This effect is a consequence of the underlying performance characteristics in hover and cruise states.

The SoS framework highlights interesting aircraft architecture effects and propagation between multiple levels. For example, as shown by Fig. 13, the Tiltrotor architecture has the largest MTOM variation between the Multi and Single sizing missions, whereas the Compound Helicopter architecture has the least difference. However, when this system (aircraft) level result is propagated to the SoS level for the respective fleet sizes; the success percentage appears to be the same for the two aircraft architectures, but the difference can be seen in the energy consumption by the network/fleet. Thus, the multilevel propagation of effect from System to SoS level can be observed as expected. This highlights that what matters is not only whether the architecture is successful in catering to passenger demands, it is also important to find out how effectively (with regards to energy consumption and sustainability), the passenger demand is catered in UAM SoS.

4.4. Sensitivity of reserve requirement

Cruise speed	POB	Sizing mission	Passenger demand	Technology scenario
40 m/s	4	Multi	High	*Near-term (10-min vs 20-min loiter)*

As UAM research is still in the early stages, there exists uncertainty regarding the regulations and certification requirements that will apply to eVTOL aircraft. How significant could the impact of legislation on the aircraft/SoI level be on the SoS level performance? To investigate this, a change in the aircraft reserve requirements is considered. The demanding 20-minutes loiter requirement is compared with a reduced loiter requirement of 10 minutes in Fig. 14, to understand the sensitivity of such requirement. The reduced reserve requirement improves the ability of the fleet to carry more passengers. Moreover, it can be observed that a change in the reserve requirement has a clear impact on the MoE criteria of success percentage and energy of network. At the lowest fleet size, no significant impact is observed due to this change as the system is overloaded with passenger demand and the fleet is unable to fully serve this demand (shown by annotation AB). At the highest fleet size again, no change is observed as there are significantly more aircraft deployed than needed to serve the passenger demand (shown by annotation CD). However, comparing the fleet size of 24, a near doubling of the success percentage is observed for the tiltrotor coming due to this relaxation of reserve requirement. For a fleet size of 30, the impact on success percentage of this reduction is almost negligible. For the same fleet size, a fleet composed of aircraft with 2 persons on board, an increase of 20% in success percentage is observed. The impact of a change in reserve requirement is most clearly seen in the energy used by the network where for the most energy intensive fleet size (24 aircraft) a 20% reduction is observed (denoted by annotations EF). These nonlinear effects demonstrate the need for the SoS approach as the complex interactions and snowball effects coming from aircraft/SoI level changes can have unpredictable effects on the SoS level. The change in regulation does not have a direct impact on the performance of the system, rather it is indirect. A reduced reserve requirement results in a lighter (annotation GH), more energy efficient vehicle (demonstrated by annotations IJ). This improved efficiency at aircraft/SoI level is seen in the SoS level through the improvements to the MoE criteria. Lastly, this change in reserve requirement means that the multirotor concept converges to a MTOM lower than 3175 kg.

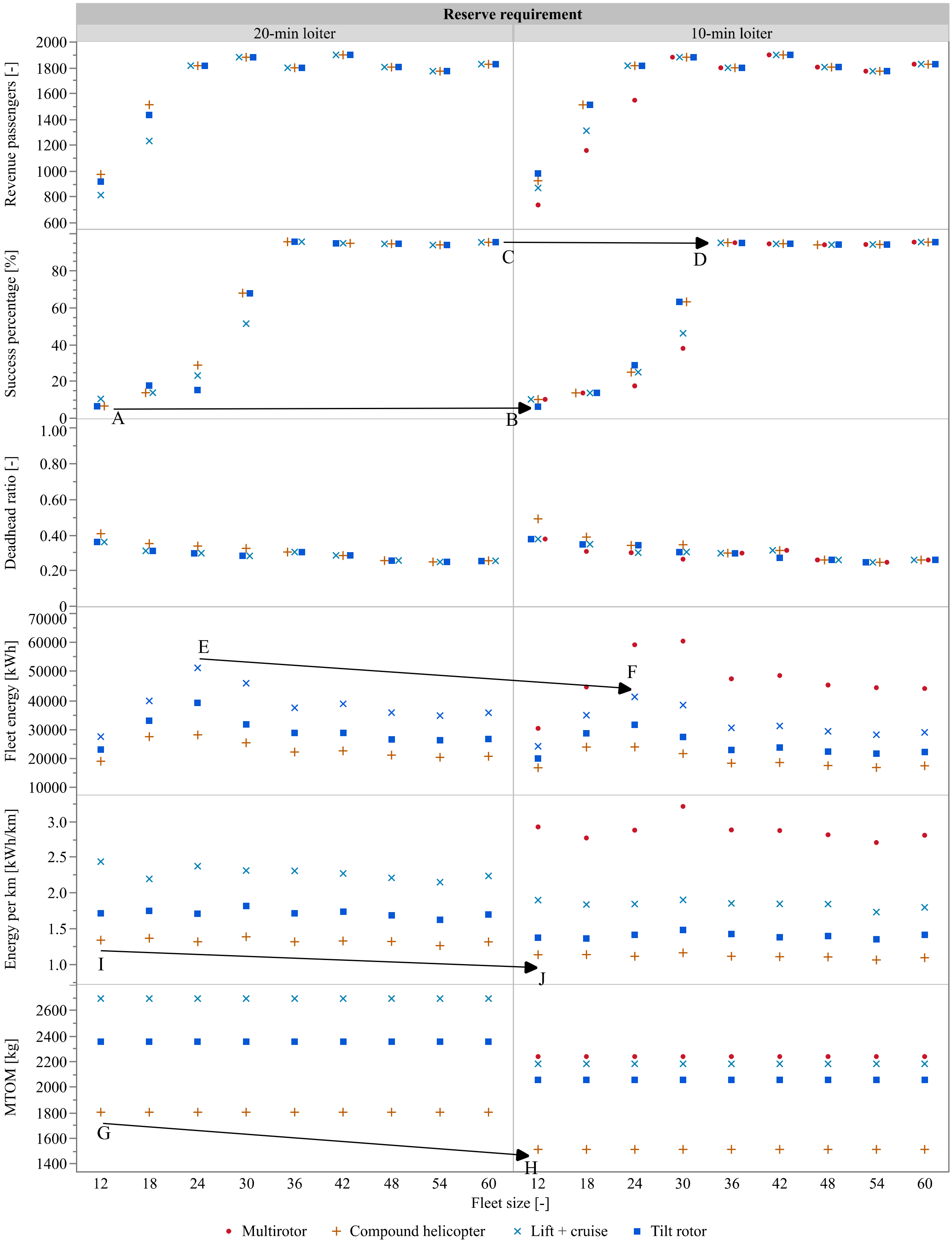


Fig. 14. Sensitivity of regulatory reserve requirement.

4.5. Sensitivity of charging technology

Cruise speed	POB	Sizing mission	Passenger demand	Technology scenario
40 m/s	2	Multi	High	*Near-term (250 vs 500 kW charging)*

From Fig. 15 it can be observed that in general, the impact of doubling the recharging power in the near-term scenario is rather small. The faster recharging does not provide a solution to the SoS, which is overwhelmed by the high passenger demand in combination with the deployment of low passenger capacity aircraft. However, there are some aircraft architecture specific findings. As soon as the fleet size can handle the high passenger demand, impacts on the most energy demanding aircraft architecture, the multirotor, can be seen. While the multirotor could not keep up with all other architectures in the low recharging power scenario, the higher charging power between flying missions or battery swapping definitely enables this aircraft architecture to lead to similar performance in the SoS. This can be seen at a cruise speed of 40 m/s and fleet sizes of 54 aircraft and higher (shown by annotations A&B). Furthermore, it can be stated that fleets consisting of high L/D aircraft architectures are not much affected by the increase of charging power. Lastly, the impact on the energy of the network is indirect and is due to the difference in deadhead ratio observed at the higher fleet sizes for the two charging powers.

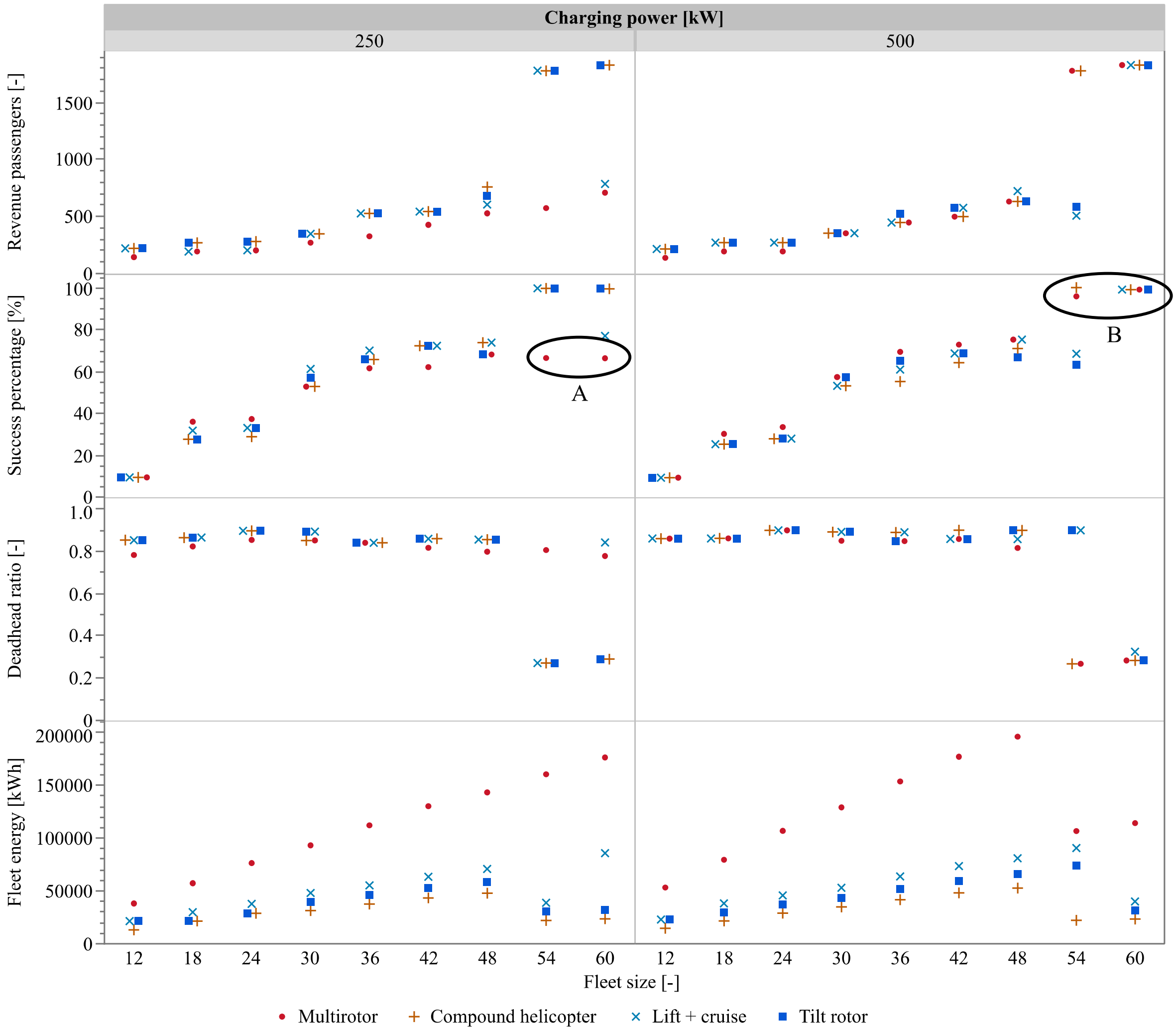


Fig. 15. Sensitivity of charging power technology.

4.6. Sensitivity of technology scenarios

Cruise speed	POB	Sizing mission	Passenger demand	Technology scenario
40 m/s	4	Multi	High	*Near-term vs far-term*

The impact of shifting the time frame and, therefore, using optimistic technology and sizing assumptions is clearly visible throughout all the shown parameters (see Fig. 16). From a SoS perspective it can be seen that smaller fleet sizes can serve all the demand, which is only 42 aircraft in the far-term instead of 54 aircraft in the near-term scenario (shown by annotations A&B). Here, the fleet of 42 aircraft can reach close to success percentage of 100. The deadhead ratio reduces drastically from about 0.8 to only 0.25 at 42 aircraft in the fleet (refer to annotations C&D), while it only reached 0.3 for some aircraft architectures, i.e. high L/D aircraft architectures, in the near-term scenario (annotation E). The same drastic effect can be seen on the average load factor that jumps to a value of 0.66, which then stays rather constant (shown by annotation F&G). Lastly, considering the SoI perspective, the energy

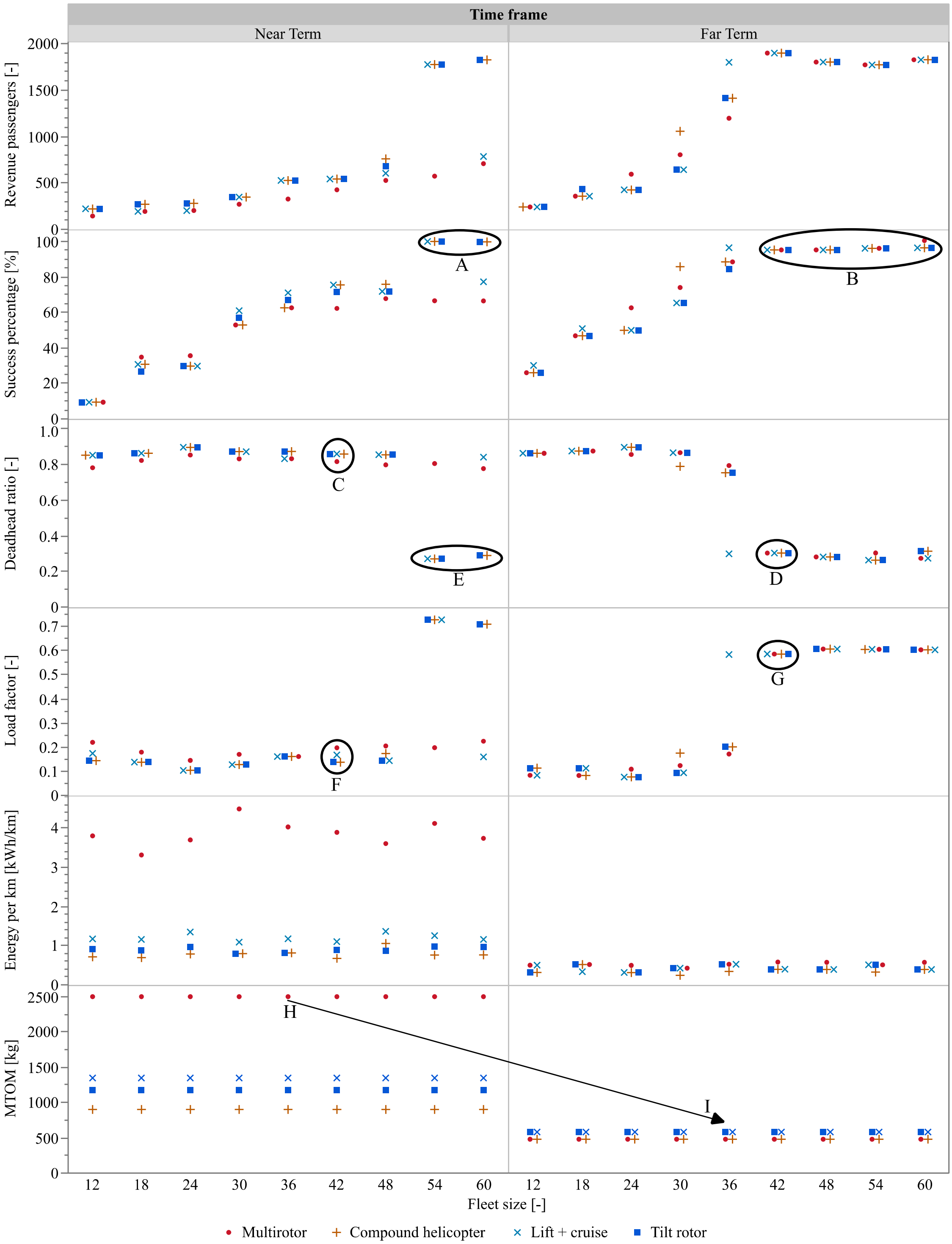


Fig. 16. Sensitivity of technology scenario.

consumption is lower in the far-term compared to the near-term scenario as can be seen from the energy per km data.

The multirotor architecture has a significantly higher (approximately 4x) energy per km usage compared to the other architectures in the near-term scenario, whereas in the far-term scenario the difference is subtler (shown by annotations HI). This suggests that as technology level is increased, the impact of the architecture may lessen at SoS level, but this varied with off-normal flying operations. Lastly, the MTOM of all architectures are significantly lower in the far-term scenario as expected due to the more favorable battery technology assumptions. From a SoS perspective the total energy used by the network decreases by about 70% between near-term and far-term scenarios for a fleet size of 60 aircraft.

4.7. Sensitivity of passenger demand

Cruise speed	POB	Sizing mission	Passenger demand	Technology scenario
40 m/s	2	Multi	*Low vs high*	Near-term

The impact of the change in passenger demand is shown in Fig. 17. In the low demand scenario, it can be seen that small fleets of up to 24 aircraft cannot serve all the demand (shown by annotation A). Also, the correlation of percentage of successful missions and deadhead ratio is clearly visible, which means that percentage of successful missions tends to increase and deadhead ratio tends to decrease with higher fleet sizes. As shown by annotation

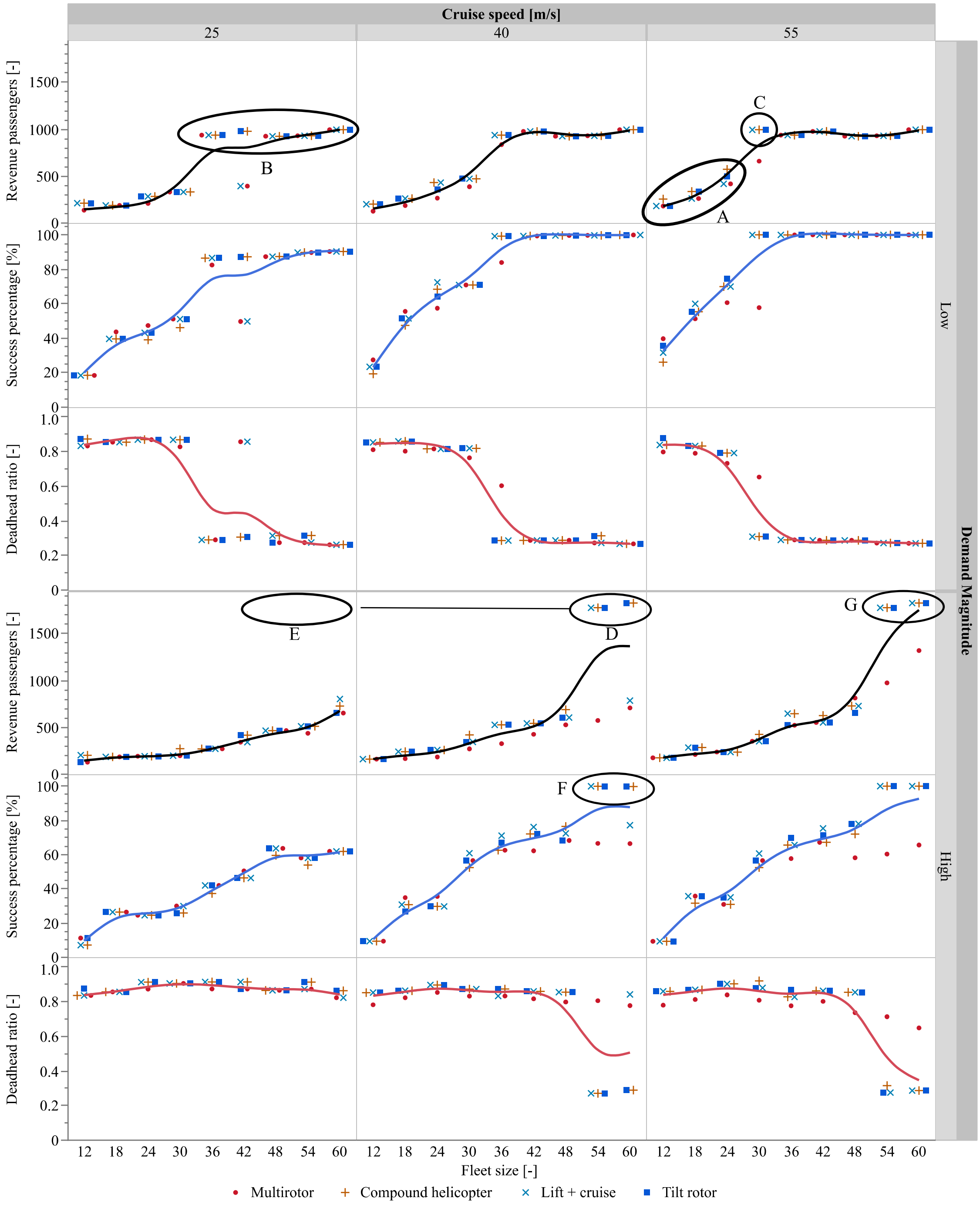


Fig. 17. Sensitivity of passenger demand variation.

B, independent of speed and aircraft architecture, all demand can be served at a fleet size of 36 aircraft. High cruise speed leads to a less sensitive SoS performance, where a rather gradual increase instead of a jump can be seen regarding the number of revenue passengers. When deploying aircraft at high L/D and high cruise speed, the passenger demand can already be fully served at a fleet size of 30 aircraft (shown by annotation C). Furthermore, the percentage of successful missions already reaches 100% in this case.

In the high passenger demand scenario, similar trends can be found with respect to correlation of percentage of successful missions and deadhead ratio. In this case, however, the aircraft flying at the slow cruise speed of 25 m/s are not able to serve all the demand and cannot even transport the same number of passengers as for the lower demand scenario (shown by annotation D, E and B). This is due to the overall high deadhead ratio, which is greater than 0.8, no matter of fleet size. The fleet reorganization leads to chaos and inefficiency. Also, the percentage of successful missions does not reach 75% in any case. Therefore, none of the fleets at a cruise speed of 25 m/s is capable of serving the high passenger demand (annotation E). In addition, annotation D shows that increasing the cruise speed to 40 m/s shows that a fleet of 54 aircraft is feasible, if high L/D aircraft architectures are considered. In that case, all the passenger demand can be served at very high percentage of success of 95% (annotation F). The corresponding deadhead ratio is reasonably low at around 20% for these fleets. The highest cruise speed of 55 m/s does not seem to lead to a more effective SoS. Even in this case, the required fleet size is 54 aircraft (shown by annotation G). As the general trends are as described for the cruise speed of 40 m/s, it seems that a cruise speed of 40 m/s is already sufficient. The doubling of the demand results in an increase of required fleet size from 30 and 36 aircraft (for 40 m/s and 55 m/s respectively) to 54 aircraft for both speeds corresponding to an increase of required fleet size of 66% and 50%. Another possibility for serving the high demand with a smaller fleet size is the deployment of aircraft with higher passenger capacity as investigated in Section 4.2.

4.8. Summary of key results

Few results below demonstrate the advantage of SoS approach towards aircraft design and operations. Some of the outcomes are nonlinear and could not be found by analytical method. These nonlinear effects demonstrate the need for the SoS simulation approach, as the complex interactions and snowball effects coming from aircraft/SoI level or technology/subsystem level changes can have unpredictable effects on the SoS level.

1. As shown in Fig. 11 and associated discussion in Section 4.1. For a given passenger demand, technology assumption and TLAR scenario for a fleet size 30, the speed increase from 25 to 55 m/s corresponds to a doubling of the success percentage (fraction of UAM passengers getting a ride within 15 min). Moreover, for a similar passenger transporting capability, a reduction of cruise speed by 55% necessitates an increase of fleet size from by 25%.
2. As shown in Fig. 12 in Section 4.2, by doubling the passenger capacity of the aircraft, the required fleet size drops by 33%. If we remove the pilot from the consideration, then the doubling of passenger capacity, would in this case mean a tripling of revenue passenger carrying capacity. In terms of the fleet's passenger carrying capability, by doubling the POB, a reduction of 55% in the required fleet size is possible.
3. Section 4.3 demonstrates the effect of sizing and aircraft architectures for a given passenger demand. As shown in Fig. 13 and associated discussion in Section 4.3, the energy used by the 'single-flight sized' aircraft UAM network is 20-45% (depending on architecture) of the 'multi-flight sized' aircraft UAM network with same fleet size.
4. As shown in Fig. 14 and associated discussion in Section 4.4. Reduction of regulation requirement from 20 min reserve loiter to 10 min, for a fleet size of 30, a fleet composed of aircraft with 2 POB, an increase of 20% in SoS mission success percentage is observed from the reduction of reserve requirement. The change in regulation does not have a direct impact on the performance of the system, rather it is indirect. This is one of the easy to comprehend nonlinear effects noted in this SoS study. In addition, the relaxation in the reserve requirement makes the multirotor a viable configuration with 4 POB.
5. From Section 4.5, the higher charging power between flights or battery swapping definitely enables a multirotor aircraft architecture to lead to similar performance to other aircraft architecture at the SoS measures of effectiveness level.
6. The investigation of two different technology scenarios, namely near- and far-term, emphasizes that present limitations by battery technology and regulations require are careful selection of the aircraft architecture in order to efficiently achieve good SoS performance (see Section 4.6). Therefore, the SoS performance strongly depends on SoI design sensitivities in the near-term, whereas a lower impact is observed for the far-term scenario due to the optimistic assumptions on battery technology and regulations.
7. From Section 4.7, the optimum fleet for a given passenger demand and Hamburg city network can be noted for near term. When deploying aircraft at high L/D and high cruise speed, the assumed passenger demand for city of Hamburg can already be fully served at a fleet size of 30 aircraft.

5. Conclusions and future work

This research article has investigated the simulation of a UAM case study in a SoS context. Therefore, a new approach for SoS aircraft design and operational simulation framework has been proposed and proof of concept has been demonstrated by sensitivity studies. The SoS design space exploration and sensitivity results for approximately 5,000 simulation points (each point simulating 24-hour operations of a homogeneous fleet) have shown the complex interaction between UAM aircraft architectures, technology assumptions, fleet operations, agent dispatching logic, and UAM throughput. This study concludes that some UAM aircraft architectures are ideal for certain operational scenarios and fleet sizes; some aircraft design architectures or technologies have a detrimental effect on UAM throughput. The ability to study the impact of a single subsystem level technology parameter such as charging power and see its impact on the overall SoS by evaluating several success criteria is not possible without this simulation driven approach.

Further sensitivity studies on the aircraft/SoI level with its impact on SoS level can be carried out. The SoS framework is robust and provides the capabilities to further optimize UAM fleet efficiency by accounting for various heterogeneous fleets, dispatching algorithms, CONOPS, and vertiport networks. For future work, the UAM SoS framework is being improved with a consortium of partners in a collaborative framework, as shown in Fig. 18, with higher fidelity aircraft design methods, onboard systems and cabin architectures, life-cycle assessment, vertiport network, and 4D-trajectories including noise considerations. Further SoS explorations regarding life-cycle assessment [26] and extended aircraft design methodologies including onboard systems [27] have already been carried out.

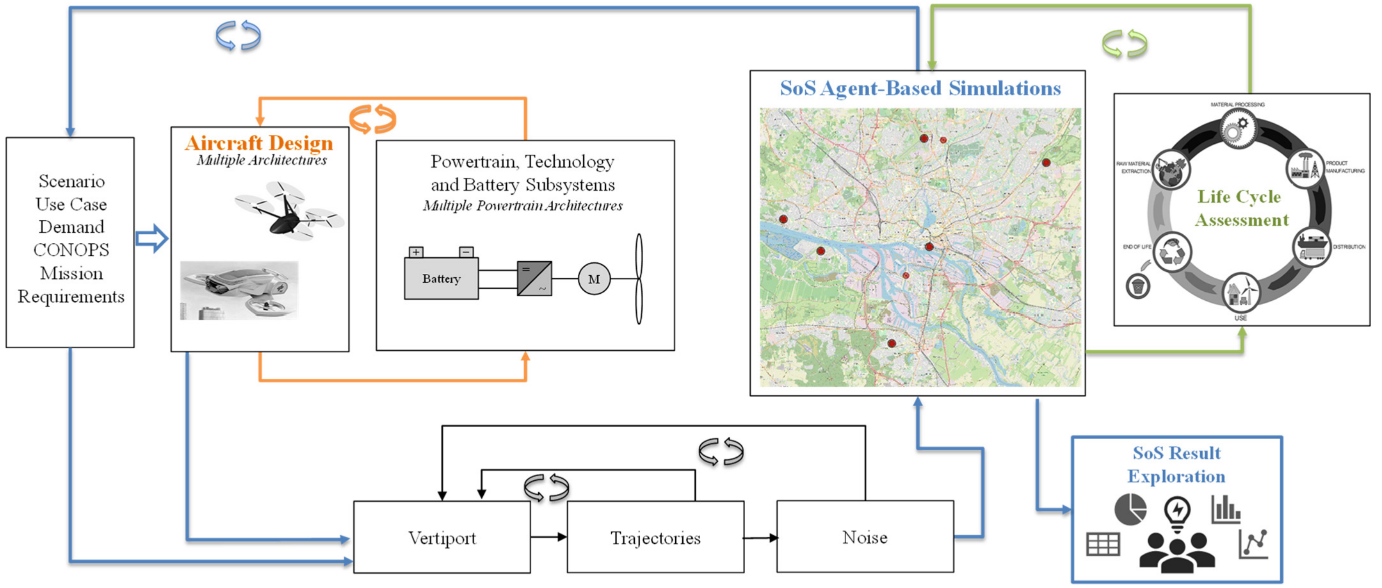


Fig. 18. Future system of systems framework for urban air mobility (development in progress).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ast.2021.107072.

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