Mission-based flight guidance for AAM taking into account energy demand

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1. Introduction:
UAM envisions a future by air taxis / eVTOLs

How can UAM ensure safe and reliable flight operations?

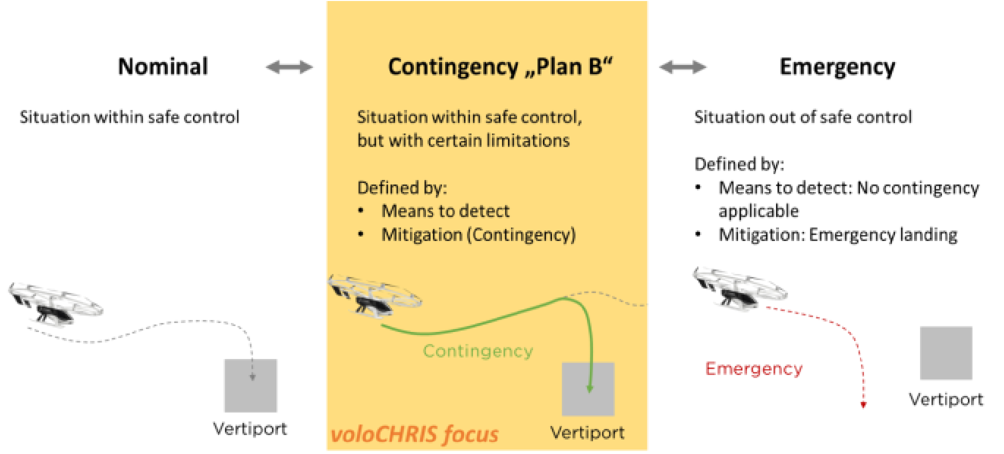
Contingency procedures

- **“Plan B"** incorporates:
  - Emergency situations
  - Holding procedures
  - Alternative routes / diversion
  - Alternative landing sites
- Backbone: Powertrain system of eVTOLs

Aim of this research:

1. What is the **realistic energy demand** for an **eVTOL** in **dynamic urban scenarios**?

2. What should be the minimum **energy reserve** for an urban mission **considering non-nominal scenarios**?



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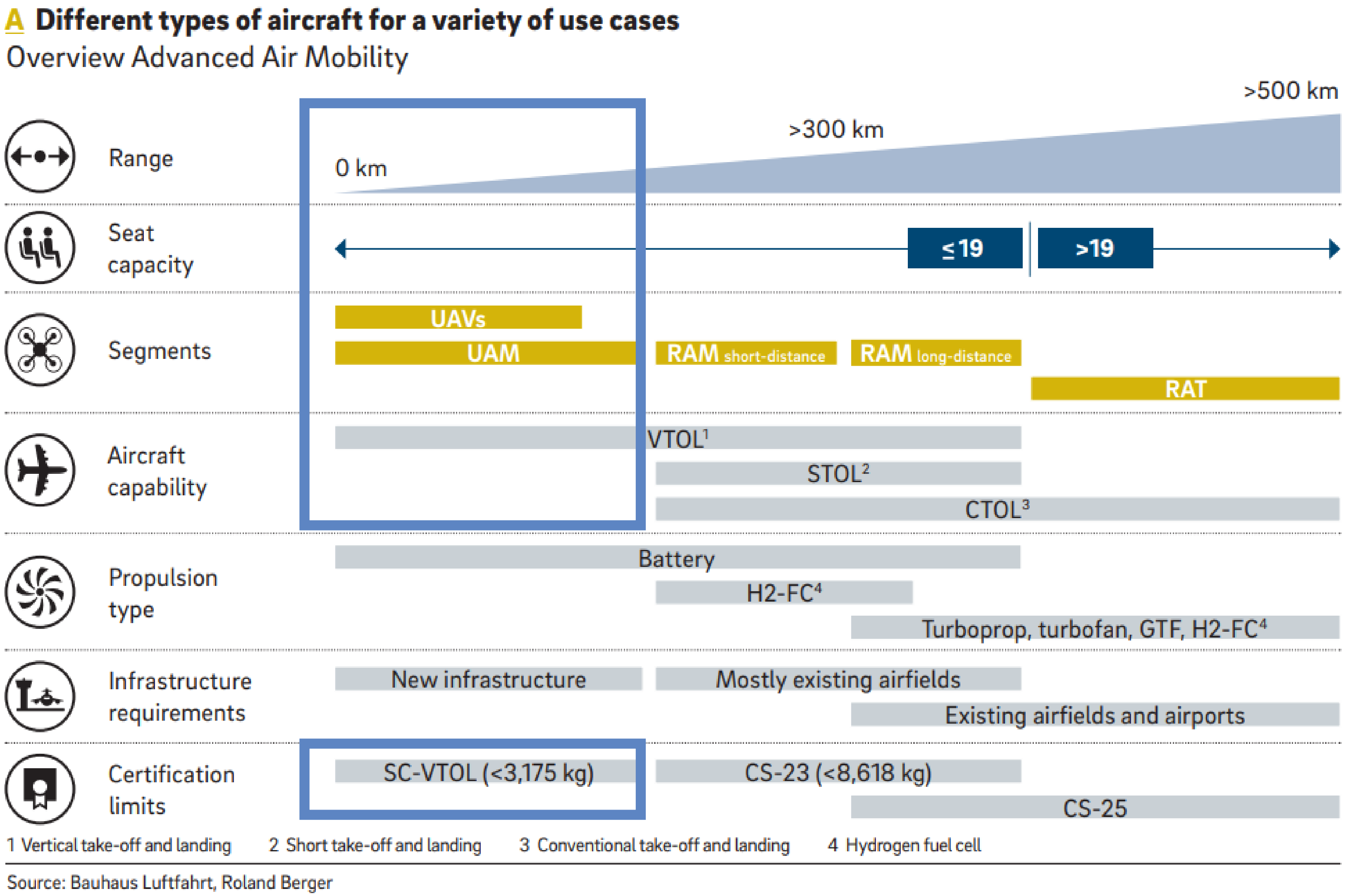
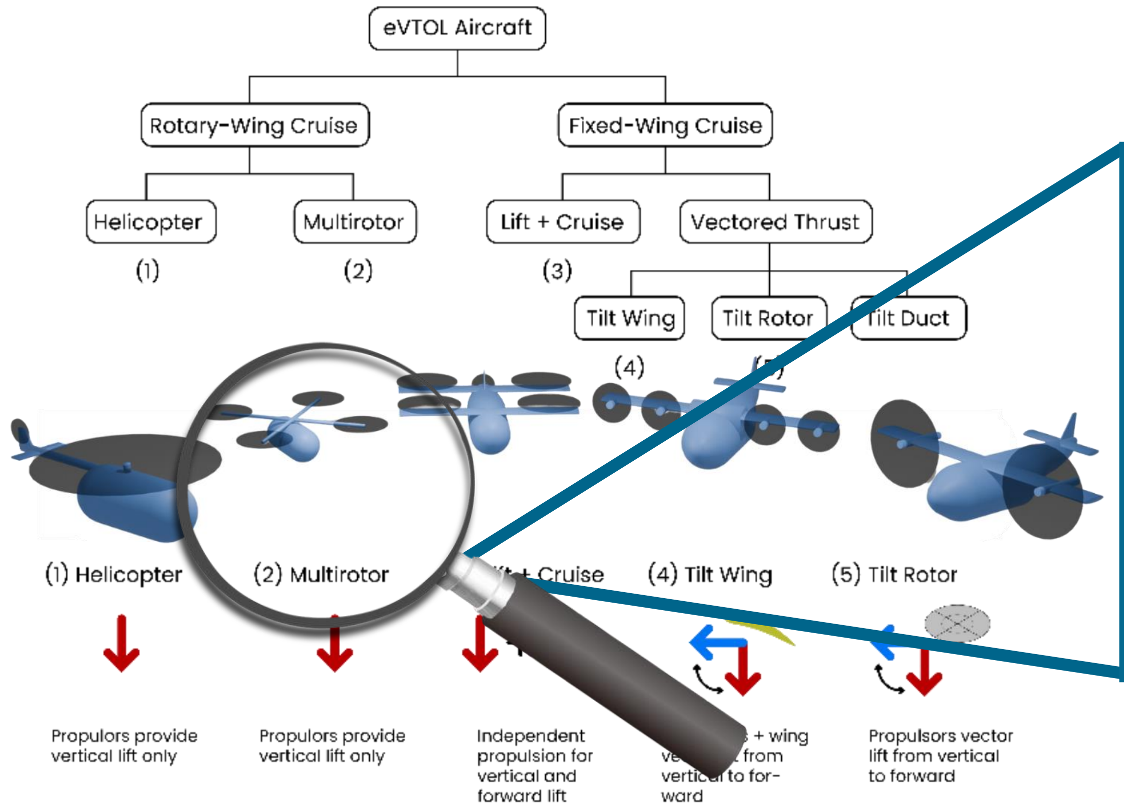
1. Introduction: Focus of PhD topic



2. State-of-the-Art: eVTOL Aircraft



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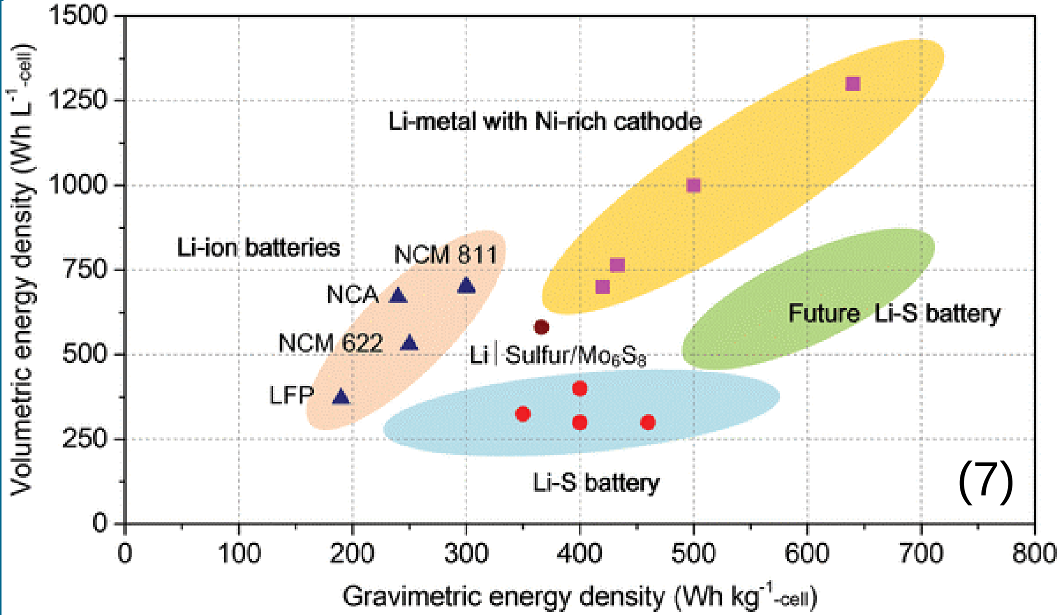
Airport Shuttle

Multicopter / quadcopter (5, 6)

2. State-of-the-Art:
Exemplary Calculation: Energy Demand for eVTOLs



Energy Capacity

$$C \geq \frac{E_{\text{flight}}}{U_{\text{sys}}}, \quad C \geq \frac{P_{\text{max}}}{\xi \cdot U_{\text{sys}}}$$

Cell discharge rate: $\xi = \frac{i_{\text{Batt}}}{c_{\text{Nenn}}}$

Energy demand during hover:

$$E_{\text{H}} = (P_0 + P_{\text{i,hover}}) \cdot t_{\text{H}}$$

Profile power: $P_0 = \rho \cdot A_{\text{r}} \cdot v_{\text{tip}}^3 \cdot \frac{\sigma}{8} \cdot C_{\text{D0}} \cdot (1 + 4.5 \cdot \mu^2)$

Tip speed ratio: $\mu \approx \frac{v_{\text{cruise}}}{v_{\text{tip}}}$

Induced power, hover: $P_{\text{i,hover}} = m_{\text{MTOM}} \cdot \text{g} \cdot \sqrt{\frac{m_{\text{MTOM}} \cdot \text{g}}{2\rho A_{\text{r}}}} \cdot \frac{1}{\eta_{\text{H}}}$

Energy demand during cruise:

$$E_{\text{C}} = (P_0 + P_{\text{i,cruise}} + P_{\text{p,cruise}}) \cdot t_{\text{C}}$$

Induced power, cruise: $P_{\text{i,cruise}} = c_{\text{i}} \cdot m_{\text{MTOM}} \cdot g \cdot \sqrt{-\frac{v_{\text{cruise}}^2}{2} + \sqrt{\frac{v_{\text{cruise}}^4}{4} + v_{\text{i,hover}}^4}}$

Parasite power, cruise: $P_{\text{p,cruise}} = 0.5 \cdot \rho \cdot f \cdot v_{\text{cruise}}^3$

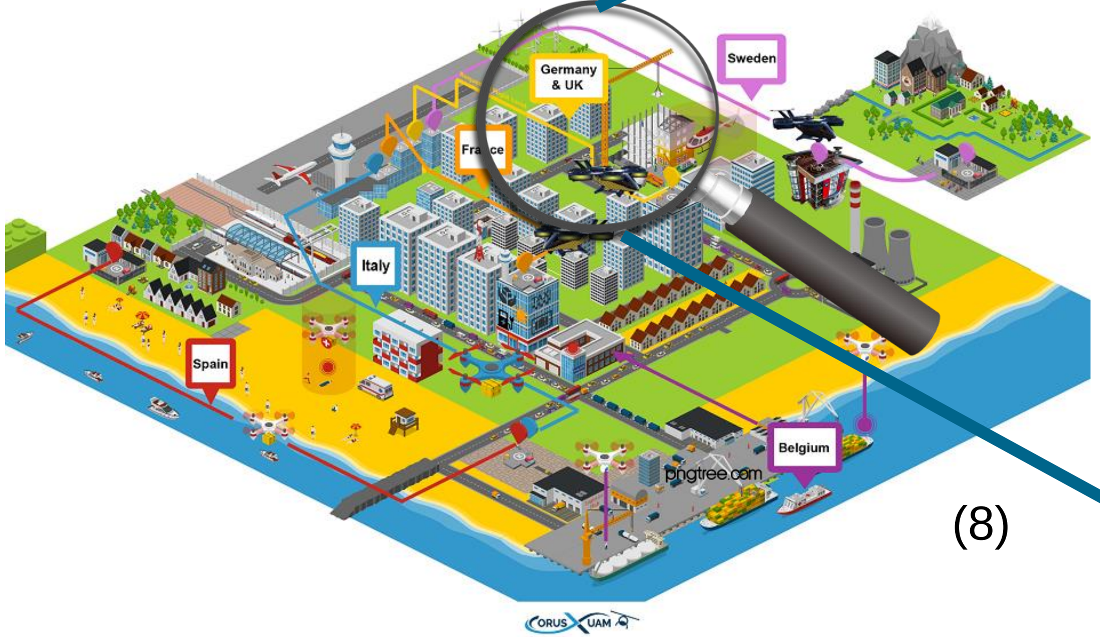
2. State-of-the-Art: UAM Concept of Operation

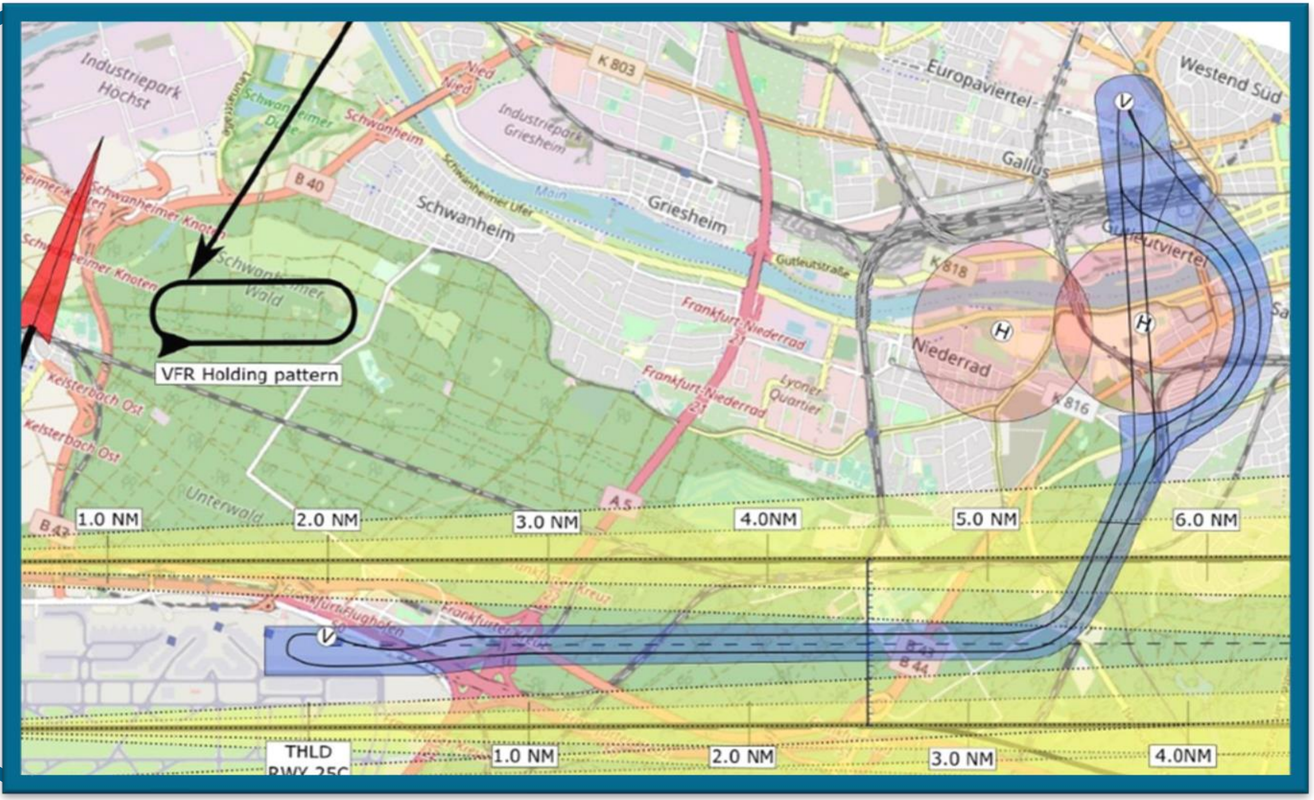
SESAR-project: CORUS-XUAM

▦ Duration: 01/2021 – 04/2023

Aim of this project

➢ Demonstration of U-space services and solutions could support UAM flight operations





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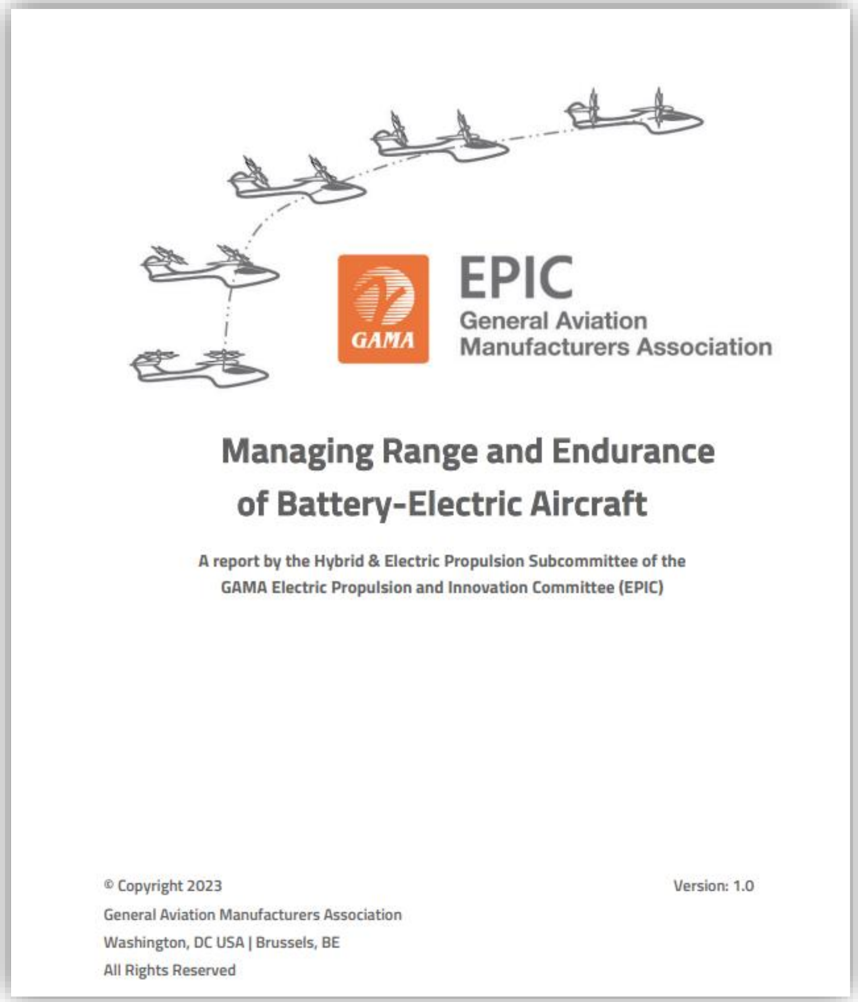
2. State-of-the-Art:
Regulatory framework for UAM

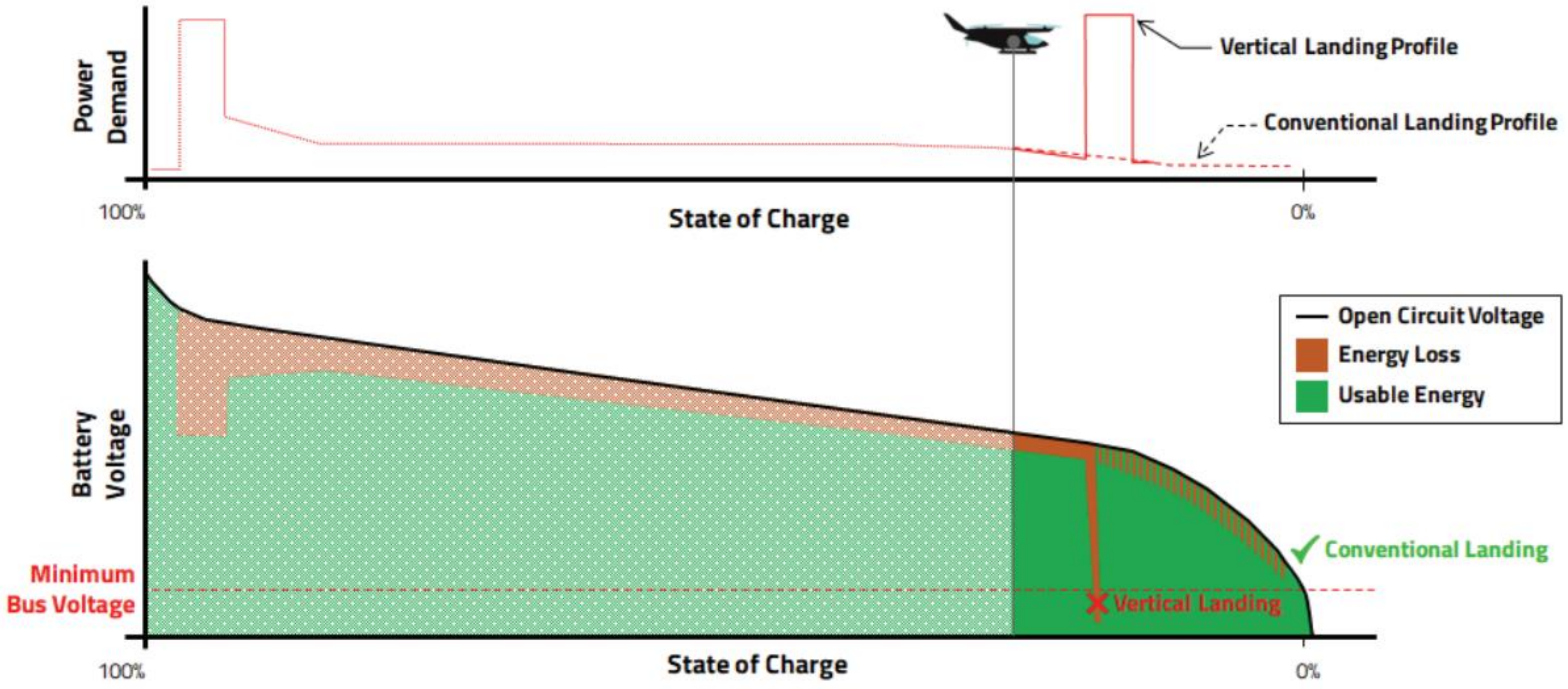


EASA – UAM Operation

- MOC-SC-VTOL
- NPA 2022-06
- Opinion No 03/2023

➢ **No regulations exist yet for the minimum energy reserve for eVTOLs**

2. State-of-the-Art:
Managing Range and Endurance by GAMA



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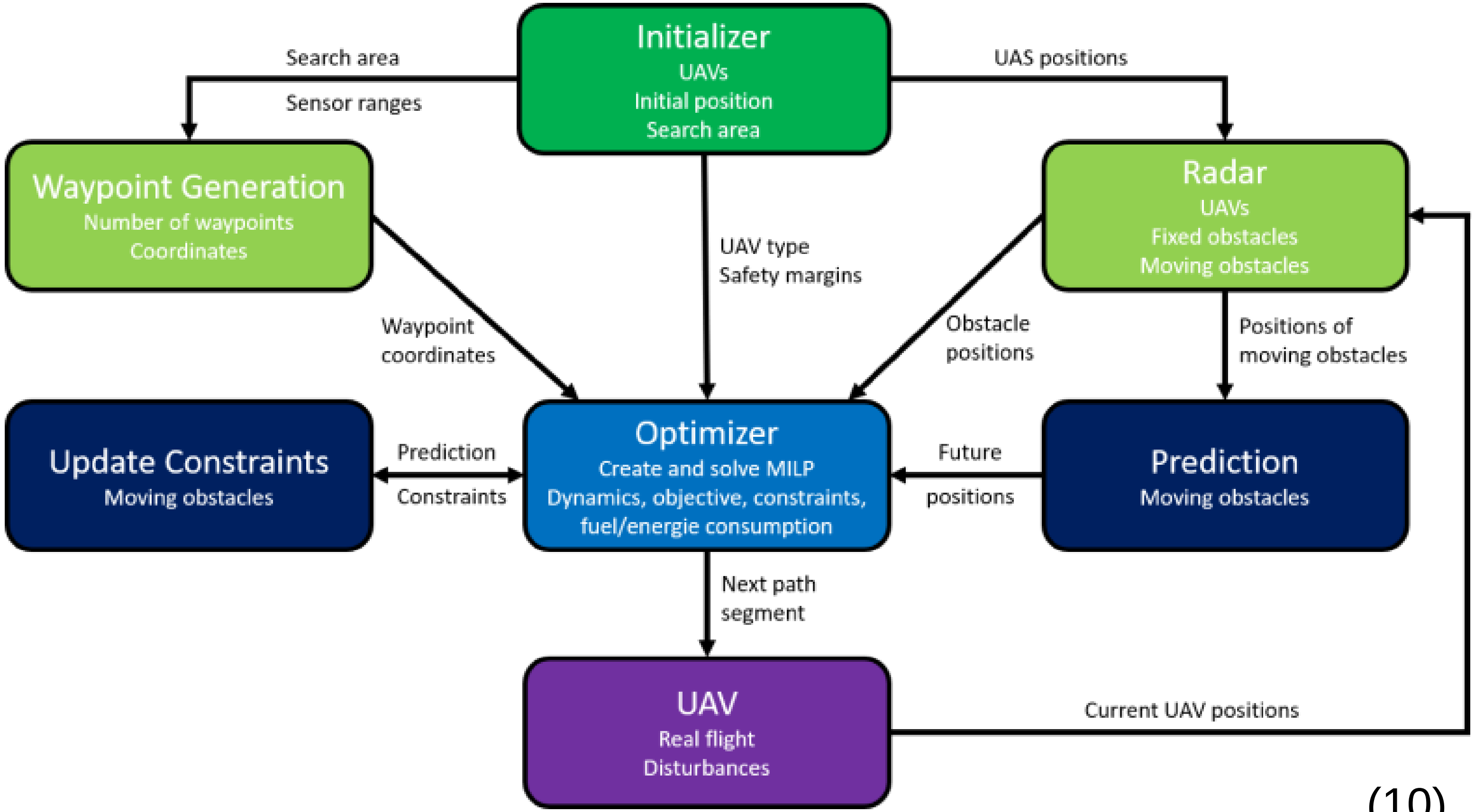
2. State-of-the-Art:
Multi-Agent Cooperative Path Planning via Model Predictive Control
ICNS Conference – 23.04.24 – Track 2 – Operational Efficiency I
C. Kallies, S. Gasche, R. Karasek



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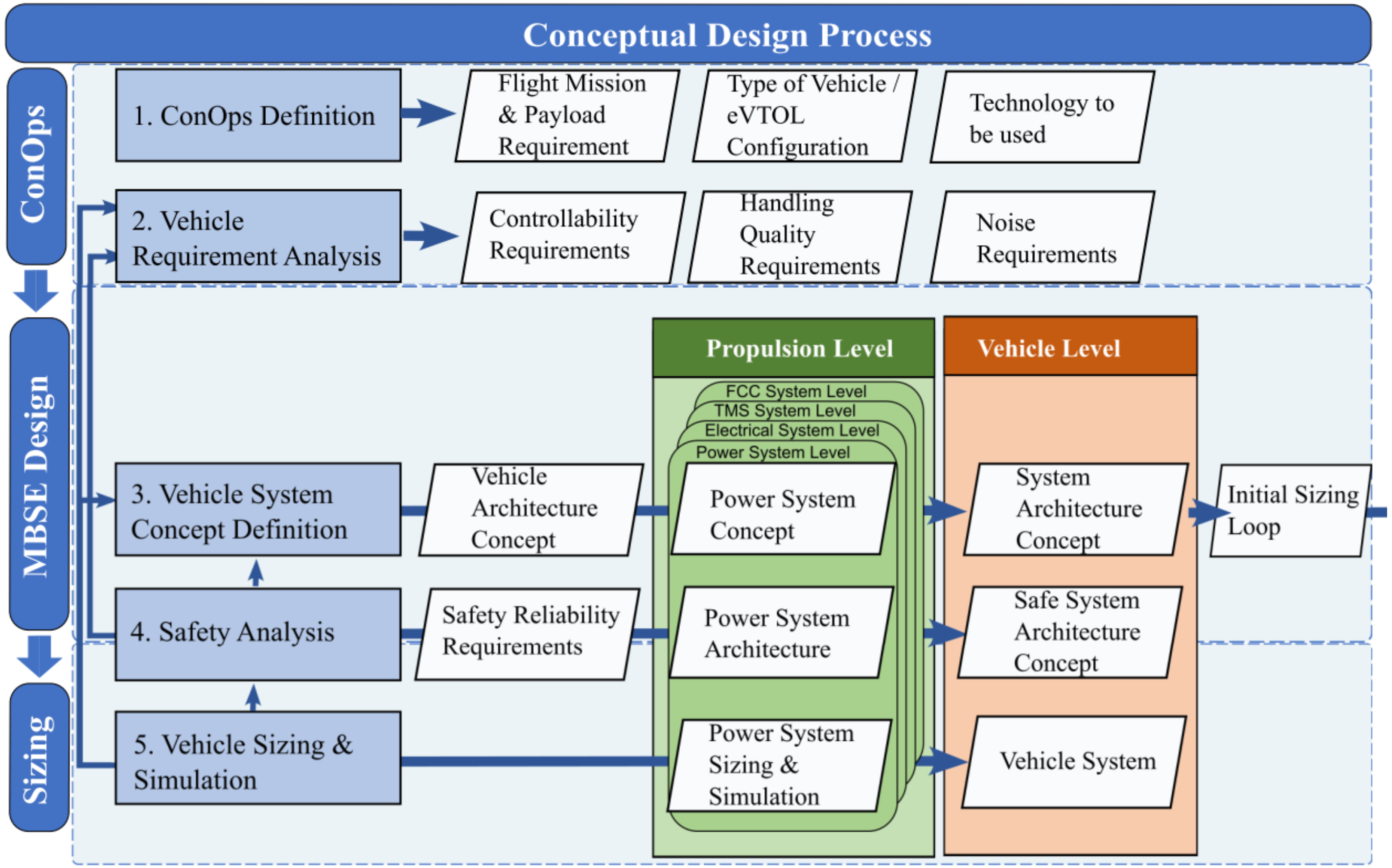
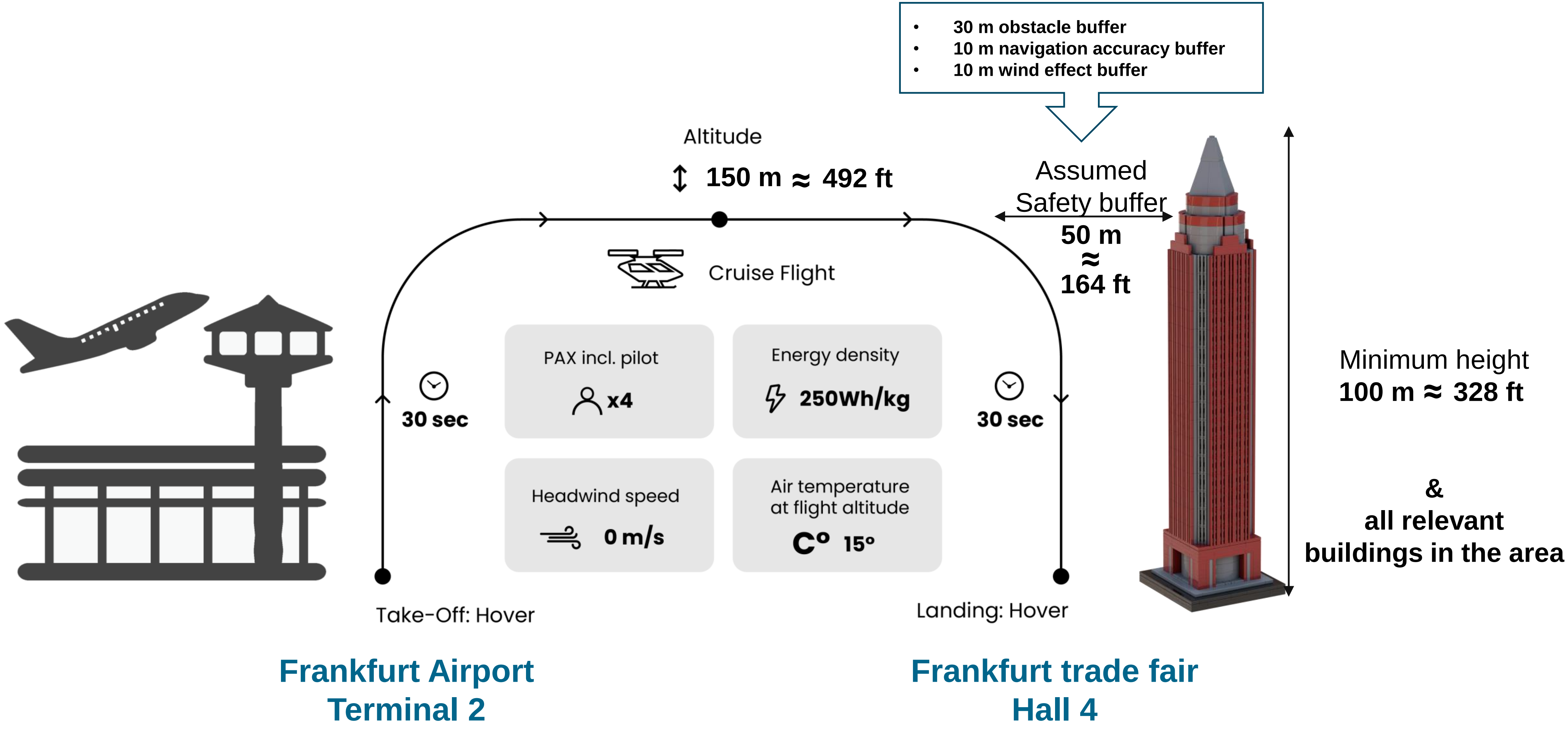
3. Methodology: Conceptual Design Process & Trajectory Based Energy Demand Analysis

Previous work | **Current work**



N. Hagag, F. Jäger, "Evaluation of the Technical Value of Powertrain Systems to Enable Safe Performance-based Flight Guidance for Urban Air Mobility," in 2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC). IEEE, 2023,

3. Methodology:
Use Case - Frankfurt Airport Shuttle



3. Methodology: Selected Vehicle

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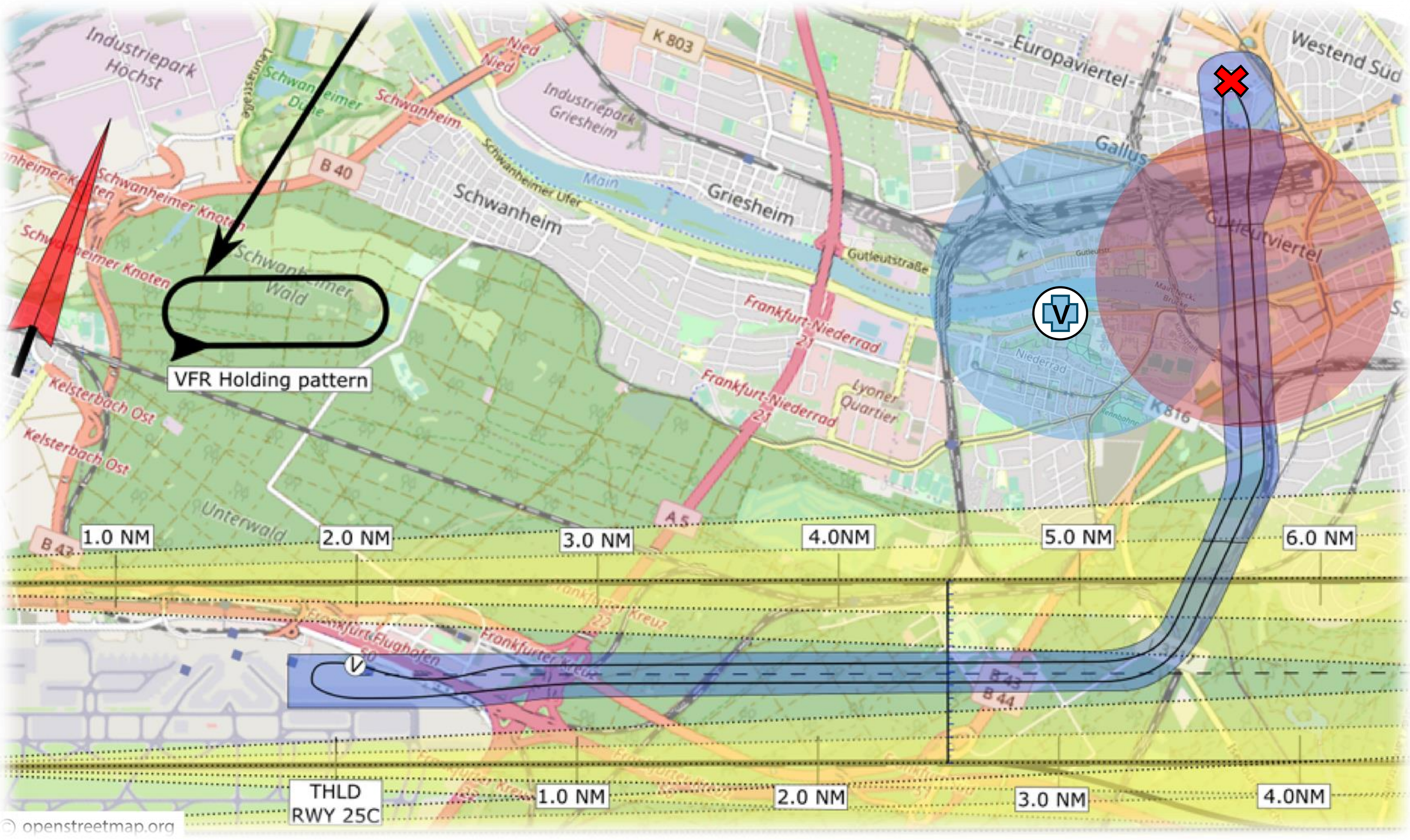
Technical characteristics	Value	Unit
Maximum take-off mass	1954	kg
Total battery weight	728	kg
Payload (4 passengers)	360	kg
Number of rotors	4	-
Rotor radius	2.64	m
Vehicle diameter	13.76	m
Number of motors	8	-
Spec. energy density of the energy system	217	$Wh\,kg^{-1}$
Battery capacity	263	Ah
Battery energy	159	kWh

3. Methodology: Selected Scenarios



Nominal flight route (REF)

No-Fly Zone (Hospital)

Moving Obstacle (Helicopter)

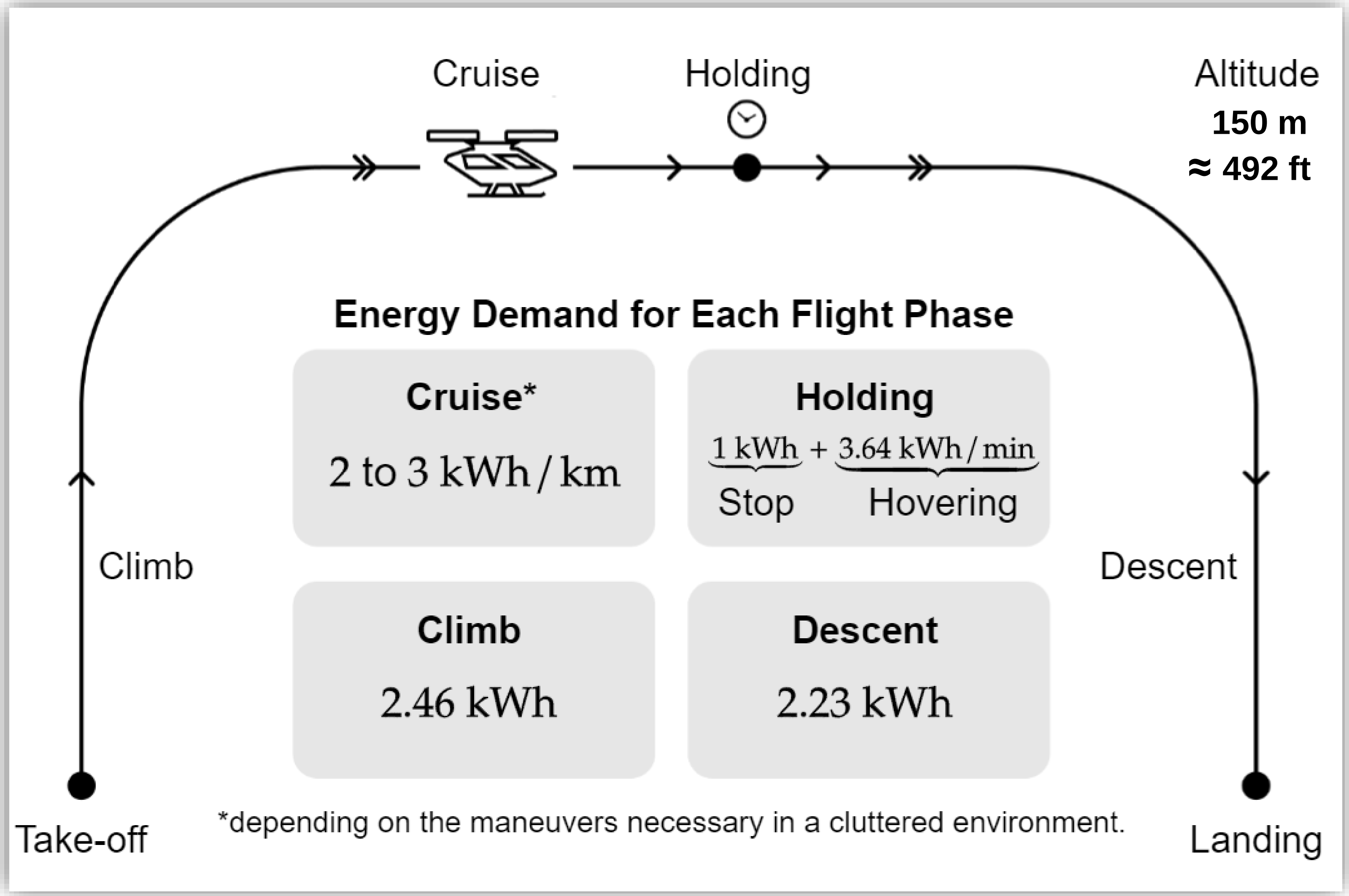
Target vertiport

Blocked target vertiport

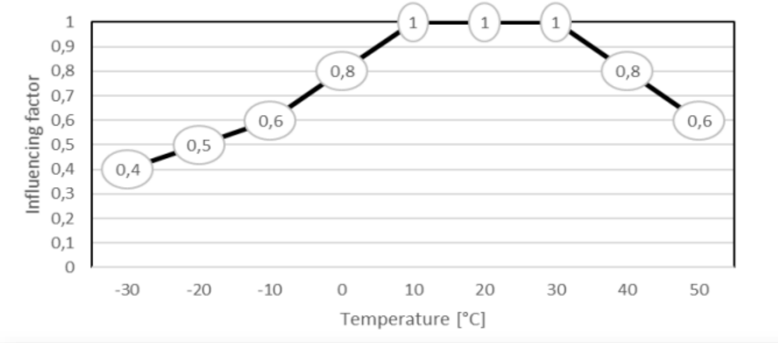
Alternative vertiport

SID / STAR for conventional aircraft

4. Key Results:
Energy Demand Analysis



5. Discussion
Limitations



Air Temperature	10,4 °C	-9,1 °C	39,4 °C	
Headwind speed	0 m/s	4,9 m/s	10,1 m/s	20 m/s

- Linear models for Energy demand analysis
- **Environmental factors** are not considered like:
  - wind
  - air temperature

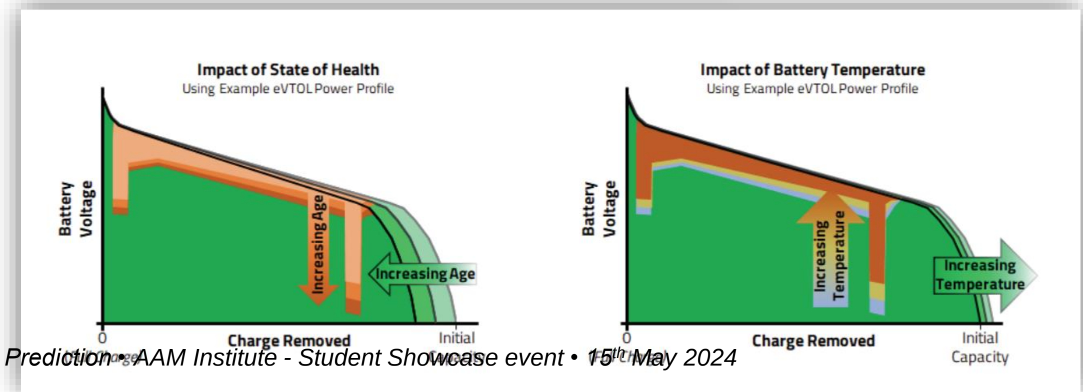
Technical characteristics	Value	Unit
Maximum take-off mass	1954	kg
Payload	360	kg
Rotor radius	2.64	m
Vehicle diameter	13.76	m
Moment of inertia about the roll axis	8700	$kg\,m^2$
Moment of inertia about the pitch axis	9495	$kg\,m^2$
Moment of inertia about the yaw axis	11 490	$kg\,m^2$
Forward flight drag coefficient	75.27	$N\,s\,m^{-1}$
Efficient cruise speed	27.77	$m\,s^{-1}$
Maximum cruise efficiency	0.9	-
Spec. energy density of the energy system	147	$Wh\,kg^{-1}$

- Vehicle parameters are approximated,

lacking **empirical validation** such as:
  - weight
  - inertia tensor
  - propeller performance

- **Battery model's validity** is affected by factors

impacting energy demand model results like:
  - ambient temperature
  - cell aging



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5. Conclusion & Outlook

Key Findings

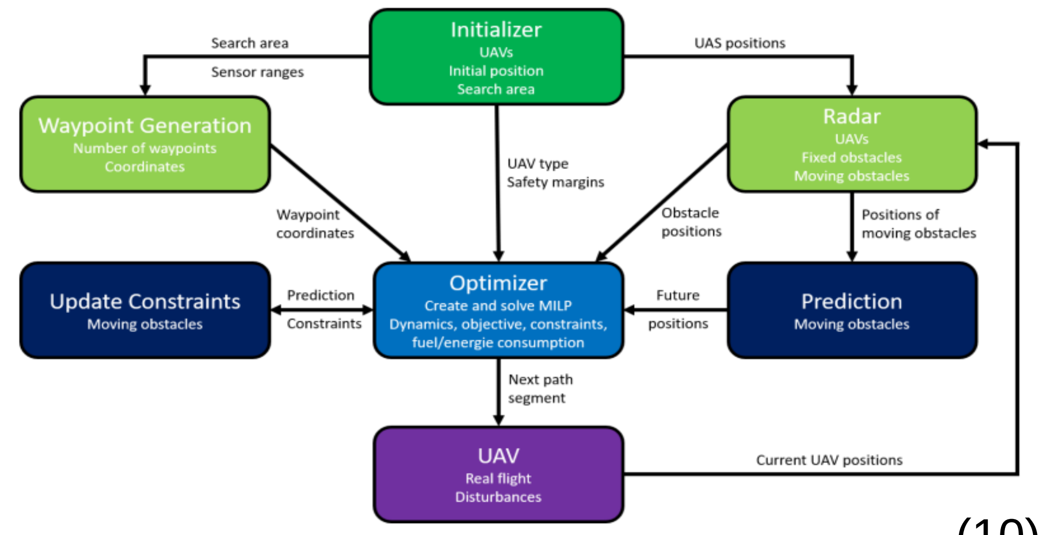
- **Brief stopover procedure consume ~ 1 kWh**
- **Hovering phase demand more energy ~ 3.64 kWh/min**
- **Climb phase was observed to require ~ 10 % more energy than decent phase**

Specific energy density, energy demand, and powertrain efficiency are crucial factors for path planning for eVTOLs

Outlook

- **Environmental factors**
- **Impact of State of Health**
- **Impact on Battery Temperature**

- **New battery technologies**
- **Energy-effienct path planning algorithm**
- **Calculation of other vehicle configurations**
  - **other powertrain systems**
  - **other performance models**
- **Different flight mission profiles**



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Thank you for your attention

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Questions?

References

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Imprint

Topic: **Energy Demand Analysis for eVTOLs in Cluttered and Dynamic Environments based on Adaptive Trajectory Prediction**

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