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On-Demand Delivery Using Fleets of UAVs with Unknown, Heterogeneous Energy Storage

Abstract—Using UAVs for goods delivery can reduce costs, increase speed, and cut emissions. To achieve these benefits, optimising UAV deployment is crucial. Here, we focus on on-demand delivery where orders arrive stochastically and should be processed promptly—neither too late, which would prolong delivery times, nor too early, which could increase the risk of failed deliveries due to insufficient battery level. Unlike previous studies, we do not rely on a specific UAV energy model and consider unknown hardware conditions. We propose a decentralised auction-based strategy that enables UAVs, given their current battery level, to decide whether and how much to bid for an order. Our multi-agent simulations demonstrate that this approach outperforms methods that require UAVs to reach a specific battery level before deployment.

I. PROBLEM FORMULATION

A Fulfillment Centre (FC) operates a fleet of delivery UAVs $U = \{u_1, \dots, u_S\}$. During period T , the FC receives orders $O = \{o_1, o_2, \dots\}$, with an average inter-arrival time $\bar{\tau}$. Each order o_i has an arrival time t_i , weight w_i , and delivery distance d_i . At any time $t \leq T$, a subset of UAVs $U_a(t) \subset U$ is available with a battery state-of-charge $SoC_j(t)$. Orders queued for delivery at t form the set $O_q(t) \subset O$, with $o_n(t)$ the next in line.

The goal is to develop a strategy to decide at each t whether to deploy a UAV from $U_a(t)$ for $o_n(t)$ or delay deployment. This strategy aims to minimise (i) average delivery time and (ii) the occurrence of Low-Battery Return-To-Home (LBRTH) events. Deploying a UAV immediately reduces delivery times but increases LBRTH likelihood, while delaying deployment decreases LBRTH likelihood but extends delivery times. The decision is complicated by uncertain UAVs' energy models and hardware conditions.

II. METHODS

a) Decentralised deployment strategy: This study presents a decentralised auction-based UAV deployment strategy implemented using the finite state machine of Fig. 1.a. UAVs with sufficient SoC enter the *Waiting* state. When orders are available, they use their bidding policy $\pi(\cdot)$ to decide whether to bid and, if so, move to the *Evaluating-Bids* state. Winning UAVs collect parcels and attempt delivery while losing UAVs return to *Waiting*. If the UAV's state of charge (SoC) drops to half the take-off value during transit, it aborts the delivery and returns. Otherwise, it will deliver the parcel before returning. Upon arrival to the FC, UAVs with low SoC enter the *Charging* state; otherwise, they enter the *Waiting* state.

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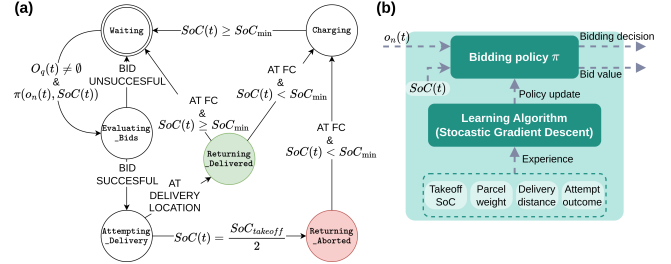


Fig. 1. (a) Finite state machine implementing the proposed deployment strategy. (b) Illustration of the online learning of the bidding policy.

b) Online learning a bidding policy: To address the deployment problem, each UAV learns a bidding policy $\pi(\cdot)$ online. The UAV uses this policy to assess if it can complete the order $o_n(t)$ given its current state-of-charge. If capable, the UAV places a bid according to its confidence value; otherwise, it abstains. After each delivery attempt, the UAV updates its policy using details such as parcel weight, delivery distance, take-off SoC, and the attempt's outcome (successful delivery or LBRTH). Following this process (illustrated in Fig.1b), the UAV indirectly learns its own energy model, considering its hardware condition.

III. RESULTS

We evaluated our deployment strategy using multi-agent simulations with a standard UAV battery model [1]. We compared it to a strategy requiring UAVs to reach a minimum SoC before deployment. As shown in Fig. 2, the proposed strategy delivers faster and reduces LBRTH events for $S = 25$, $T = 8$ weeks, and $\bar{\tau} = \{5, 10, 15\}$ minutes.

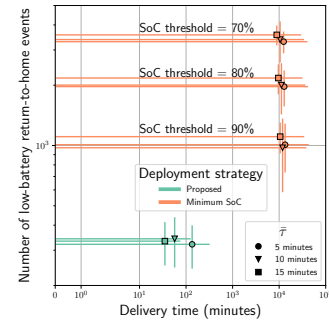


Fig. 2. Pareto optimality plot. Markers show the median values, and error bars show the 95% Confidence Interval of the median absolute deviation.

REFERENCES

- [1] K. Dorling, J. Heinrichs, G. G. Messier, and S. Magierowski, "Vehicle routing problems for drone delivery," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 47, no. 1, pp. 70–85, 2017.

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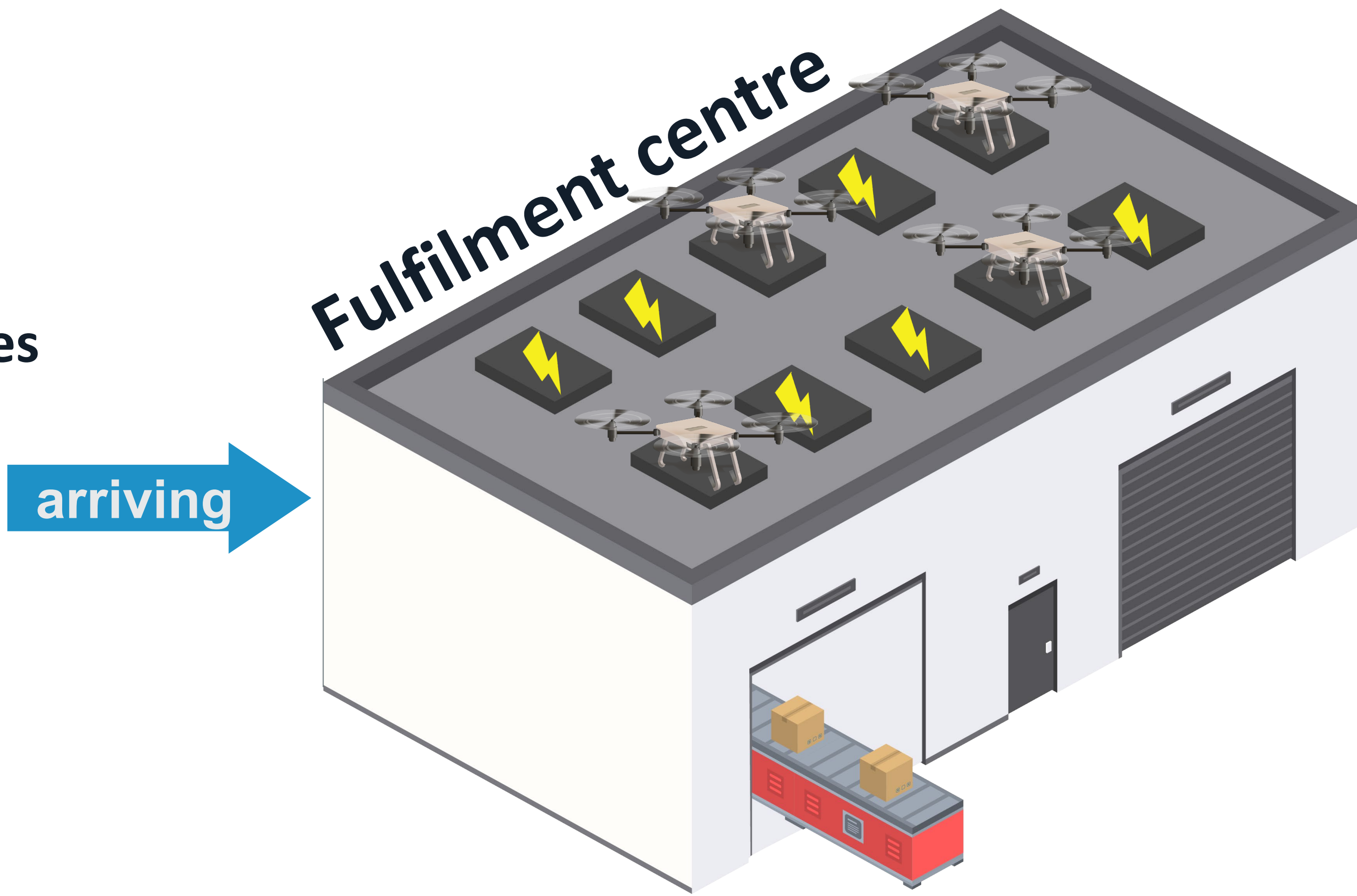
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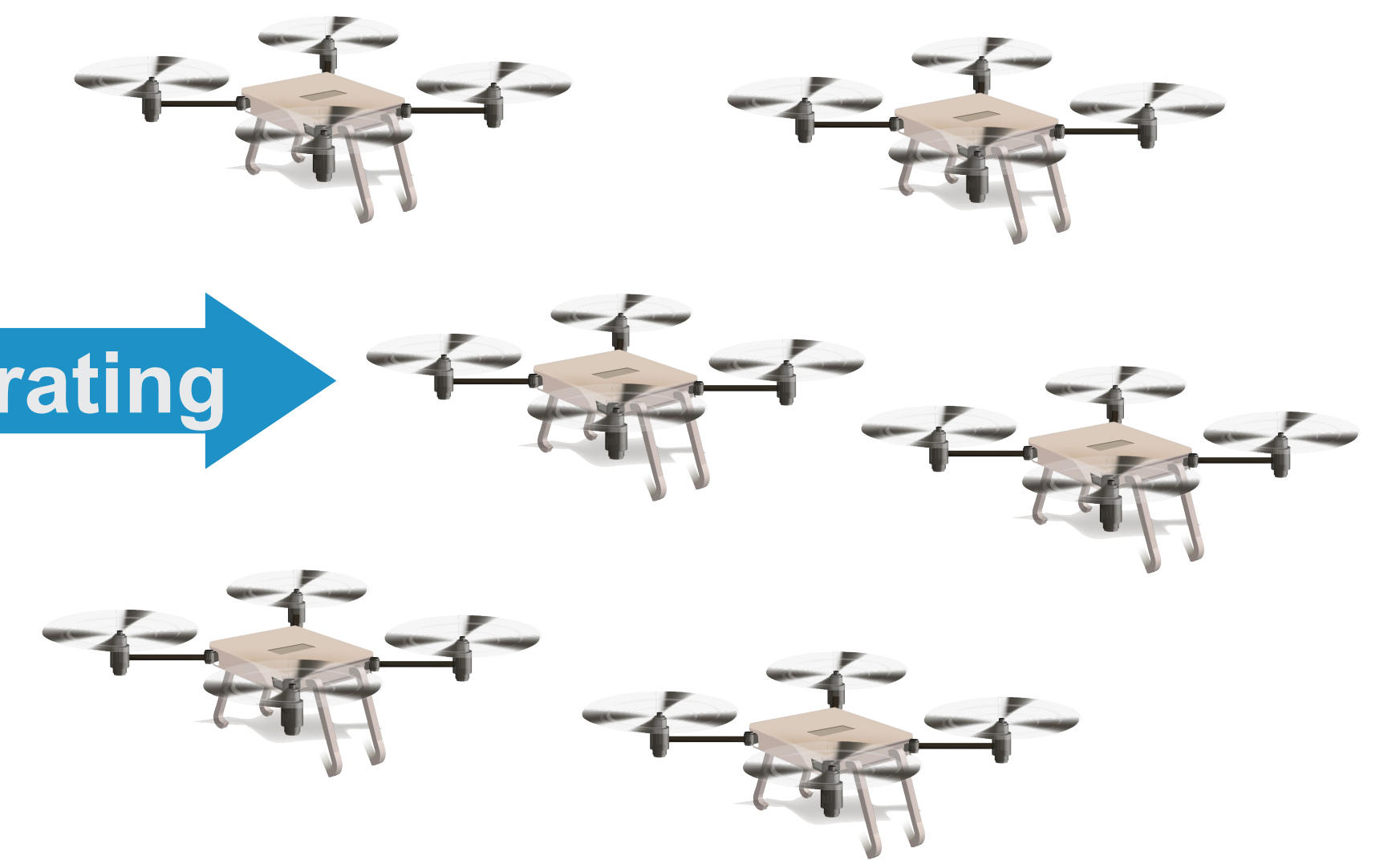
SCENARIO

Online orders

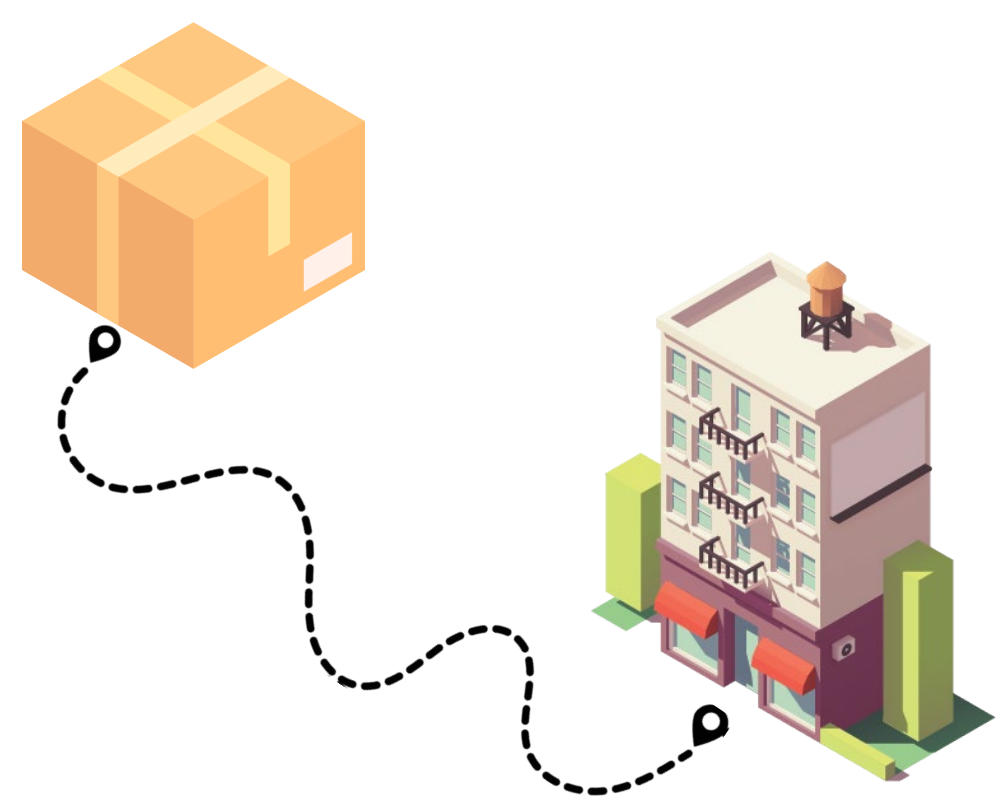
- Stochastic arrival times
- Parcel weight
- Delivery distance



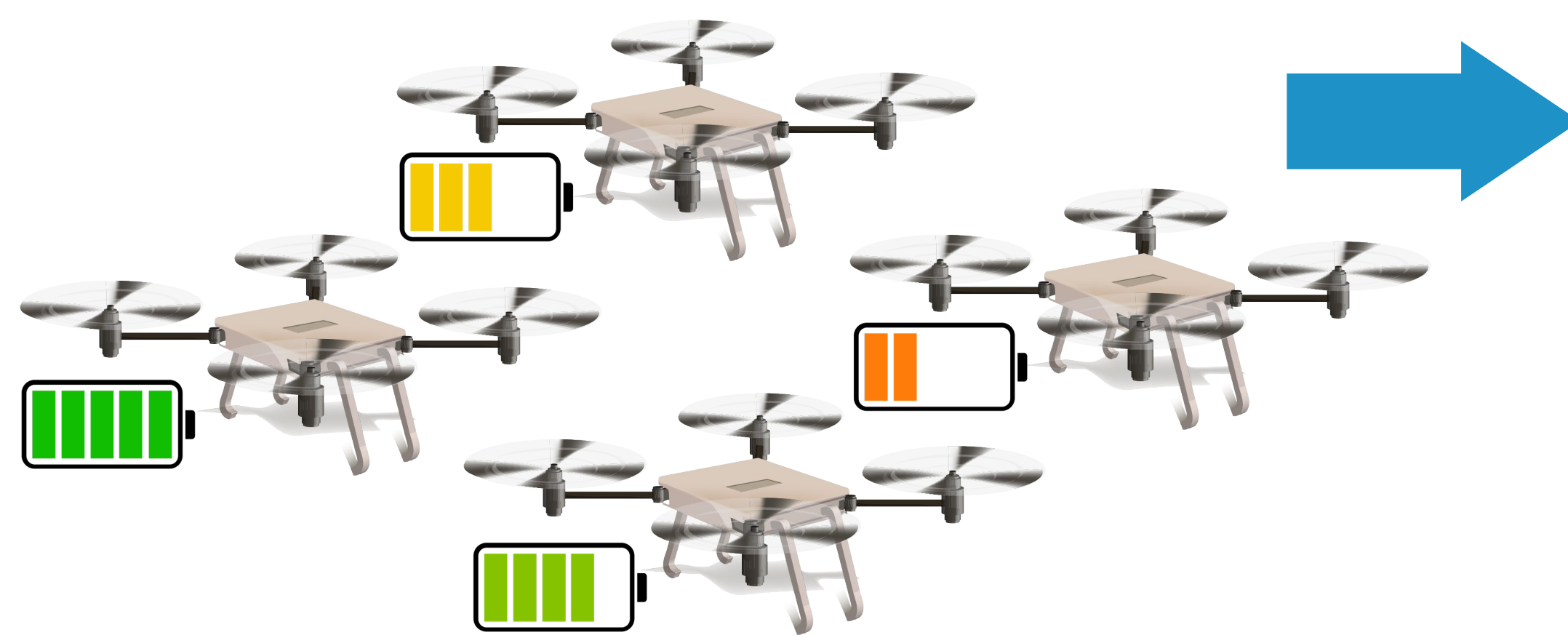
Fleet of delivery UAVs



Task: a parcel of mass m to be delivered to a distance d

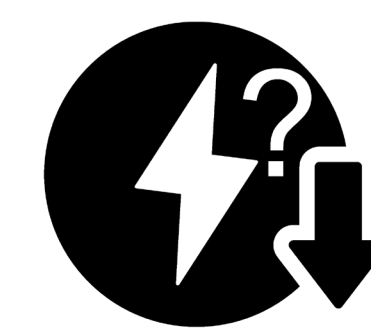


Resource: a set of UAVs, each with given charge levels c



Questions:

1. Is there UAVs ready for the task?
2. If multiple, which one to deploy?



Unknown energy consumption models



Unknown and heterogeneous battery health

PROBLEM

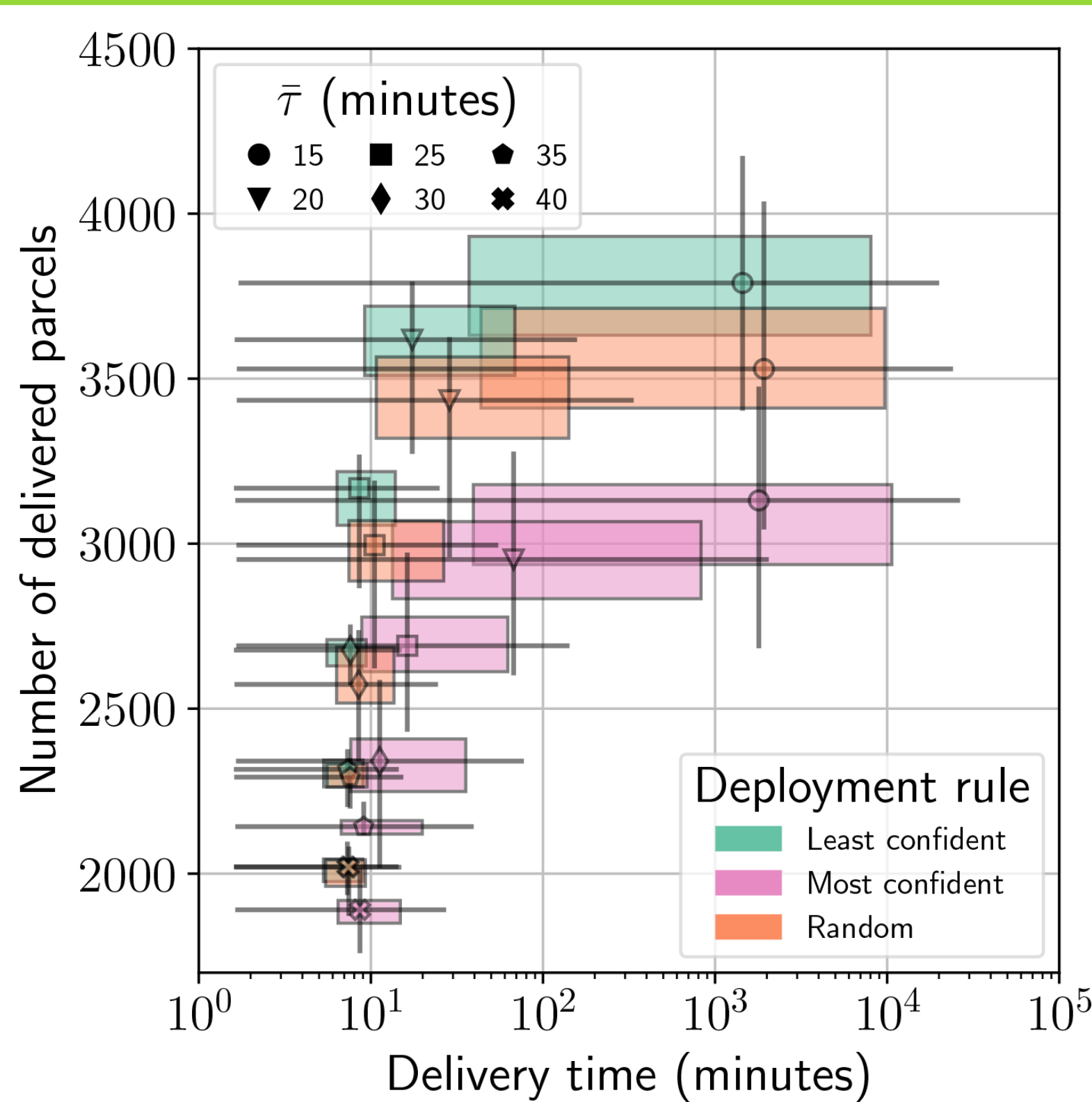
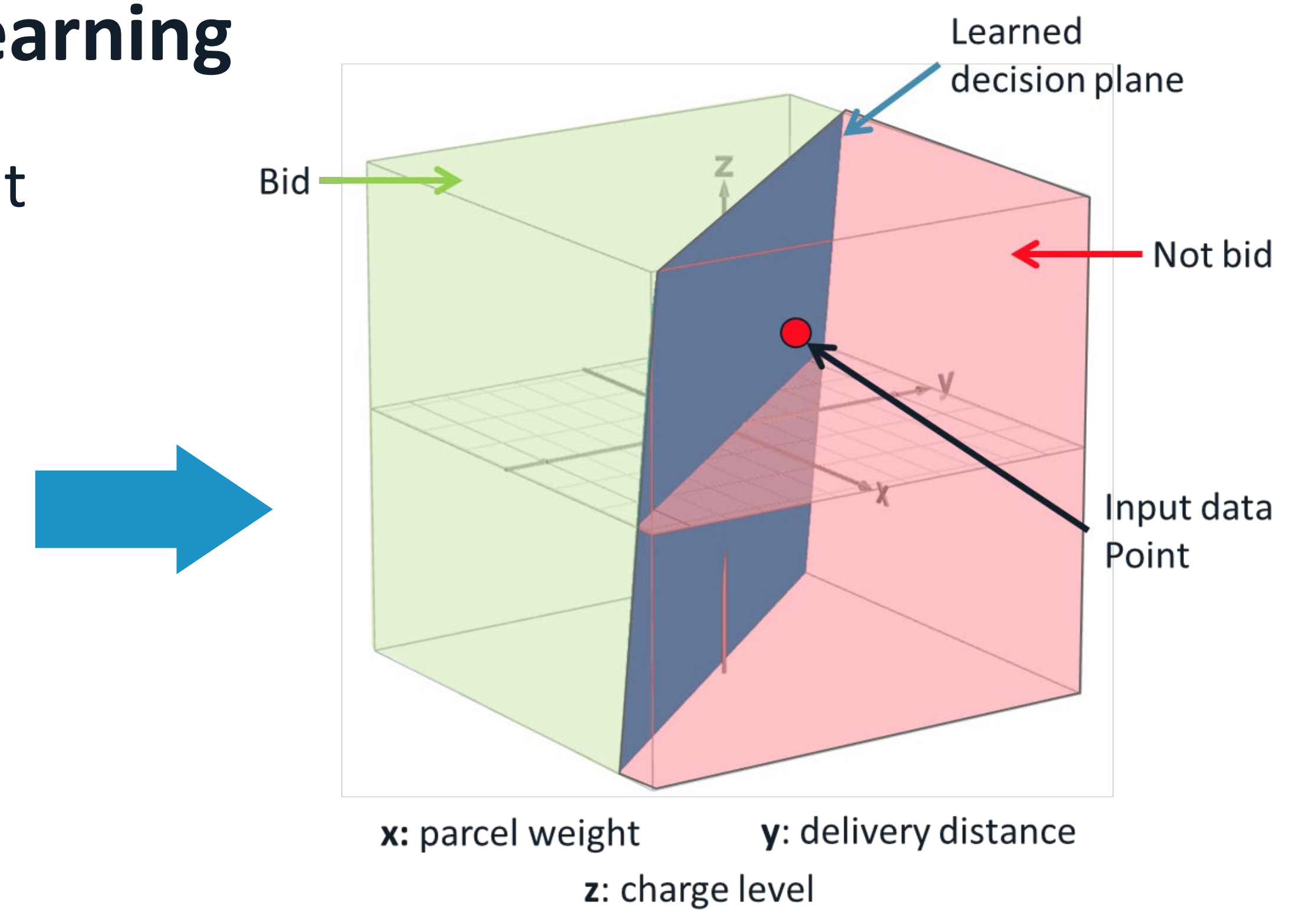
METHODS

Auction-based task allocation + Online learning

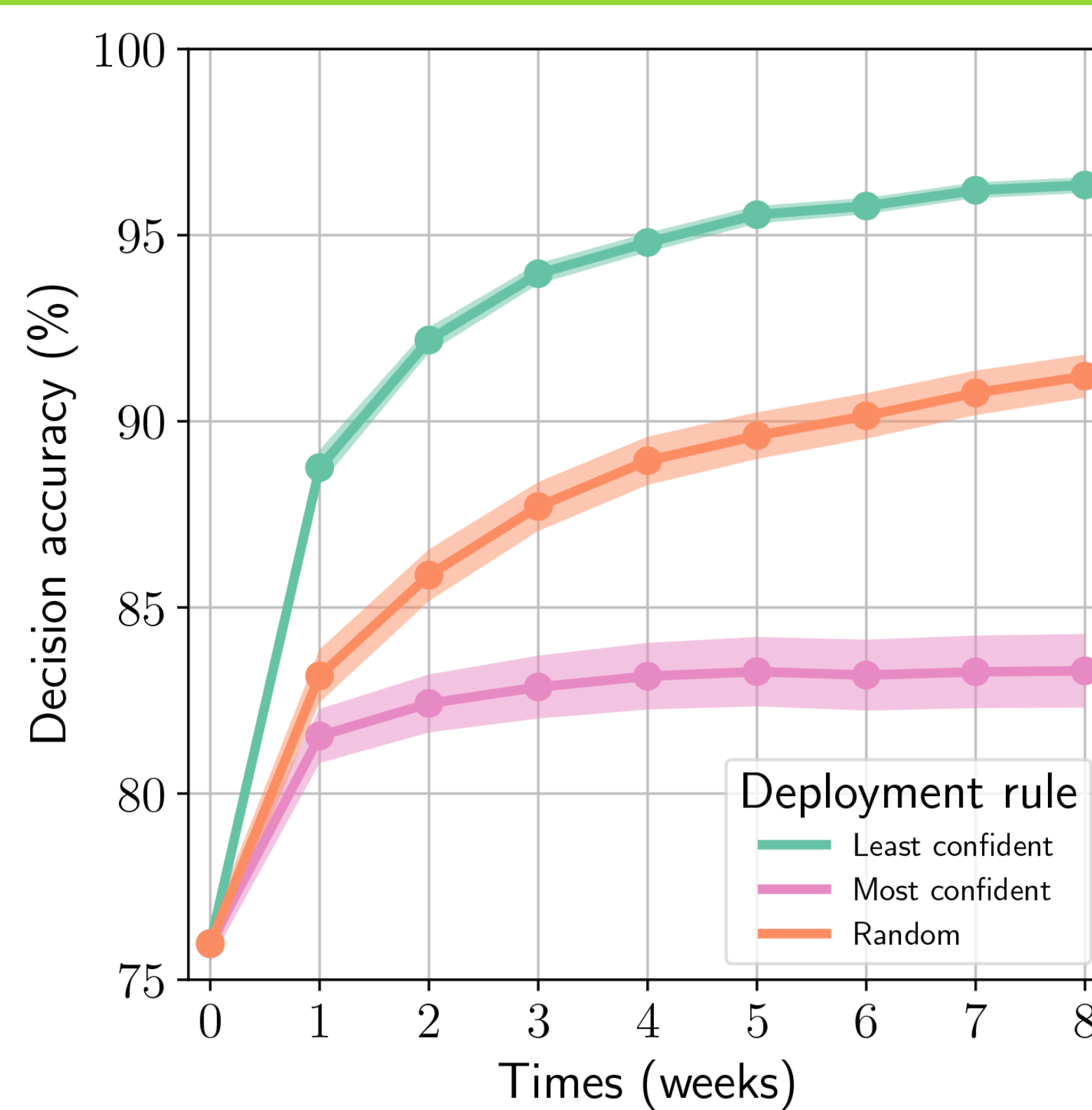


Each UAV:

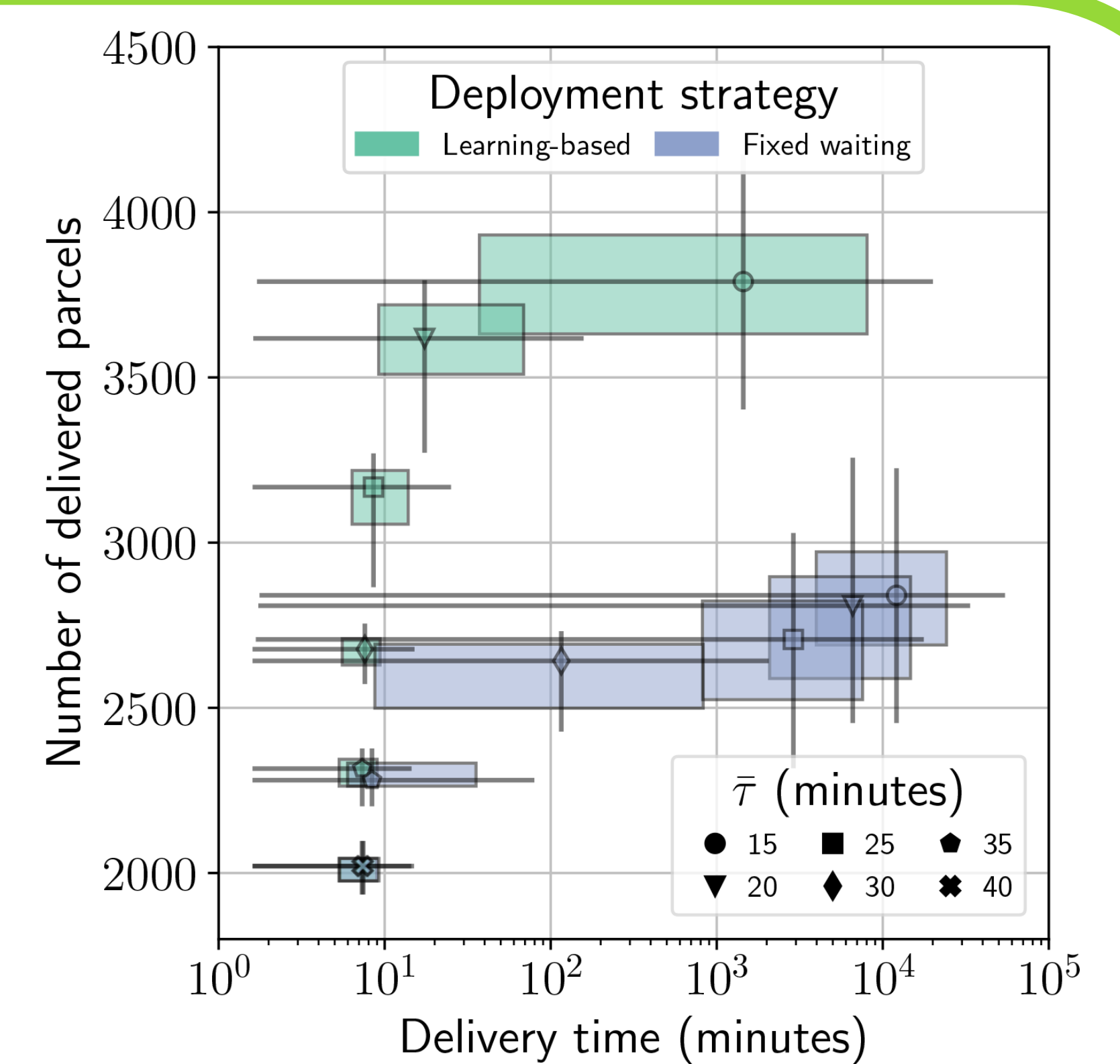
- BID**: Decides whether to bid or not given parcel weight m , delivery distance d and its current charge c
- Placing bids**: Places confidence-based bids
- Aborting**: Aborts delivery attempts when necessary
- Learning**: Adjusts bidding policy based on experience



Deploying least confident bidding UAV maximise performance



Deploying least confident allows better learning



Learning-based strategy outperforms fixed waiting

RESULTS