Innovative Uses of Drones for Logistics in Healthcare and Production

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My Background

- Degrees BSCE, MBA, PhD
- U. Pittsburgh then Auburn ISE / CSSE
- Telecommunications experience ATT
- Modeling and optimization of complex systems – current focus on logistics
- Fellow of INFORMS, IISE, and IEEE
- EIC of *INFORMS Journal on Computing* and Area Editor of *Computers & Operations Research*
- Four-time Fulbright Scholar and many current international collaborations
- Funding from NSF, NASA, DoD, DoT, NIST, Toyota, Lockheed Martin, and others
- Fun fact: graduated Dec 2022 with BA in Spanish

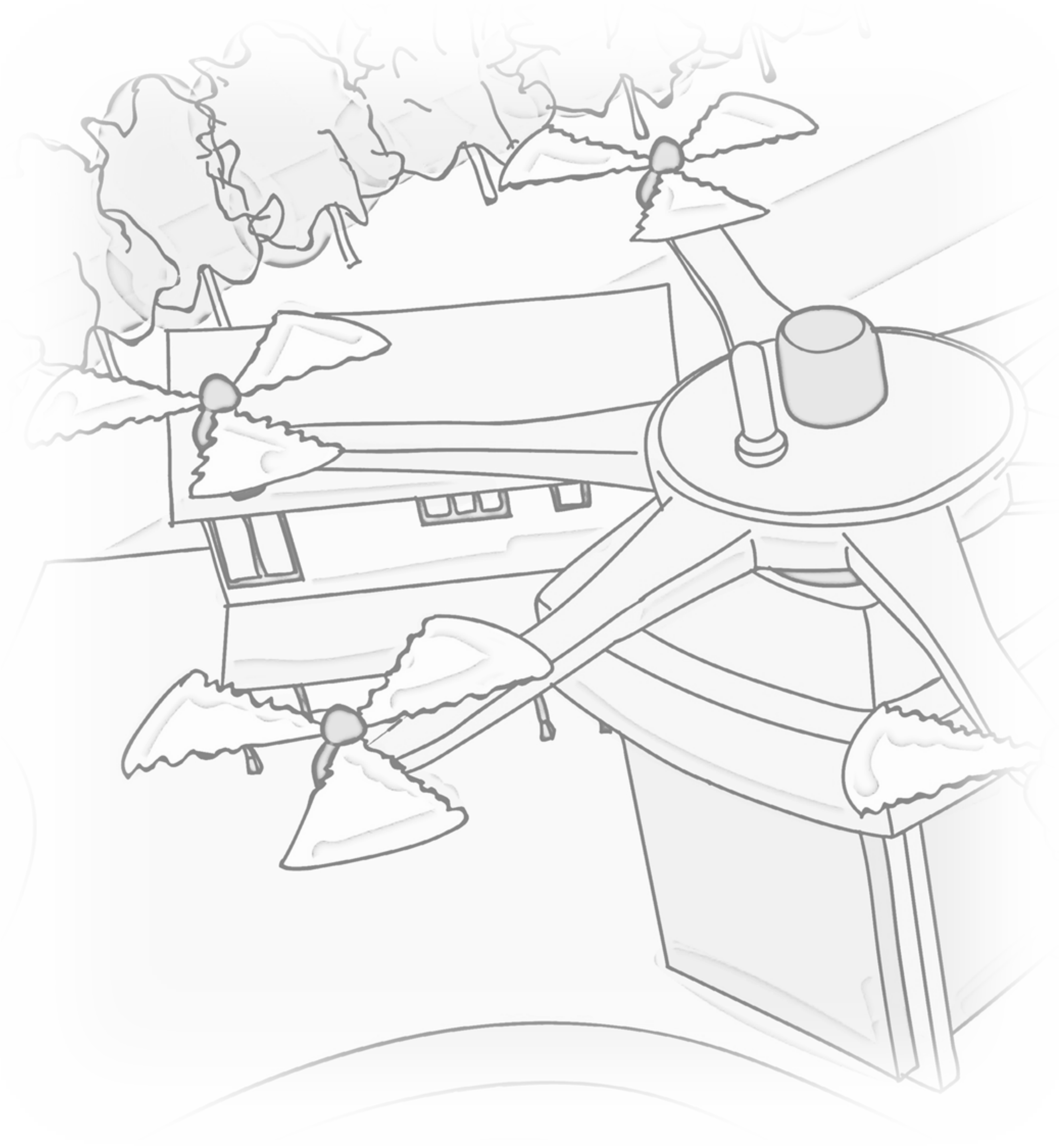
CONTENTS

DRONE-ASSISTED HEALTHCARE LOGISTICS

Challenges and innovations in rural medicine and how drones in last-mile logistics can help

DRONES FOR PRODUCTION MATERIAL HANDLING

Innovative approach to augment material handling in production environments by using drones to deliver small parts to workers



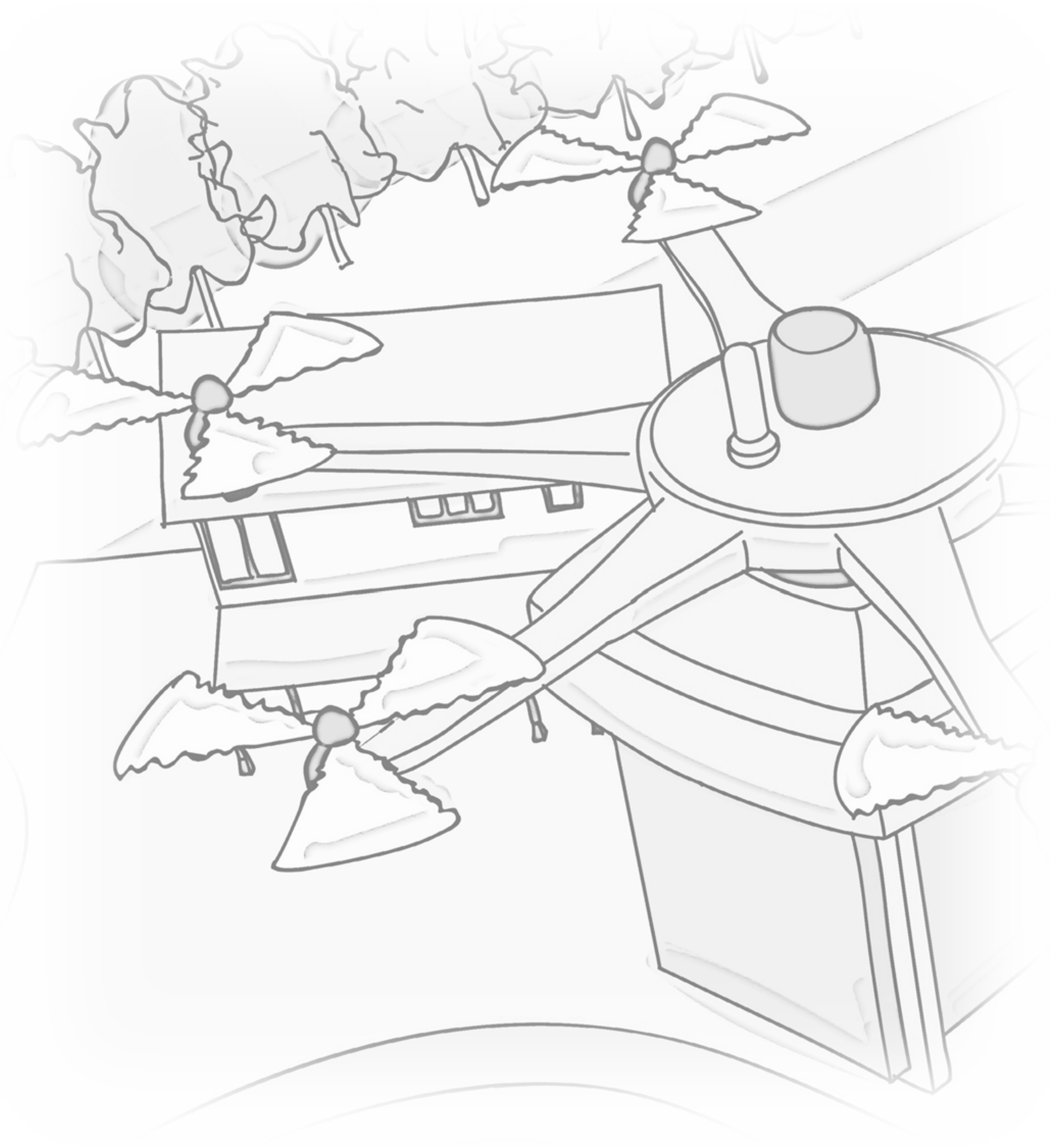
IMPACT OF LAST MILE DELIVERY

Last-mile delivery is the most expensive and time-consuming part of the e-commerce logistics chain.

Accounts for over **40%** of supply chain costs*

Without intervention by 2030:

- 36% more delivery vehicles
- Delivery traffic will increase emissions by 32%
- Congestion will increase by over 21%



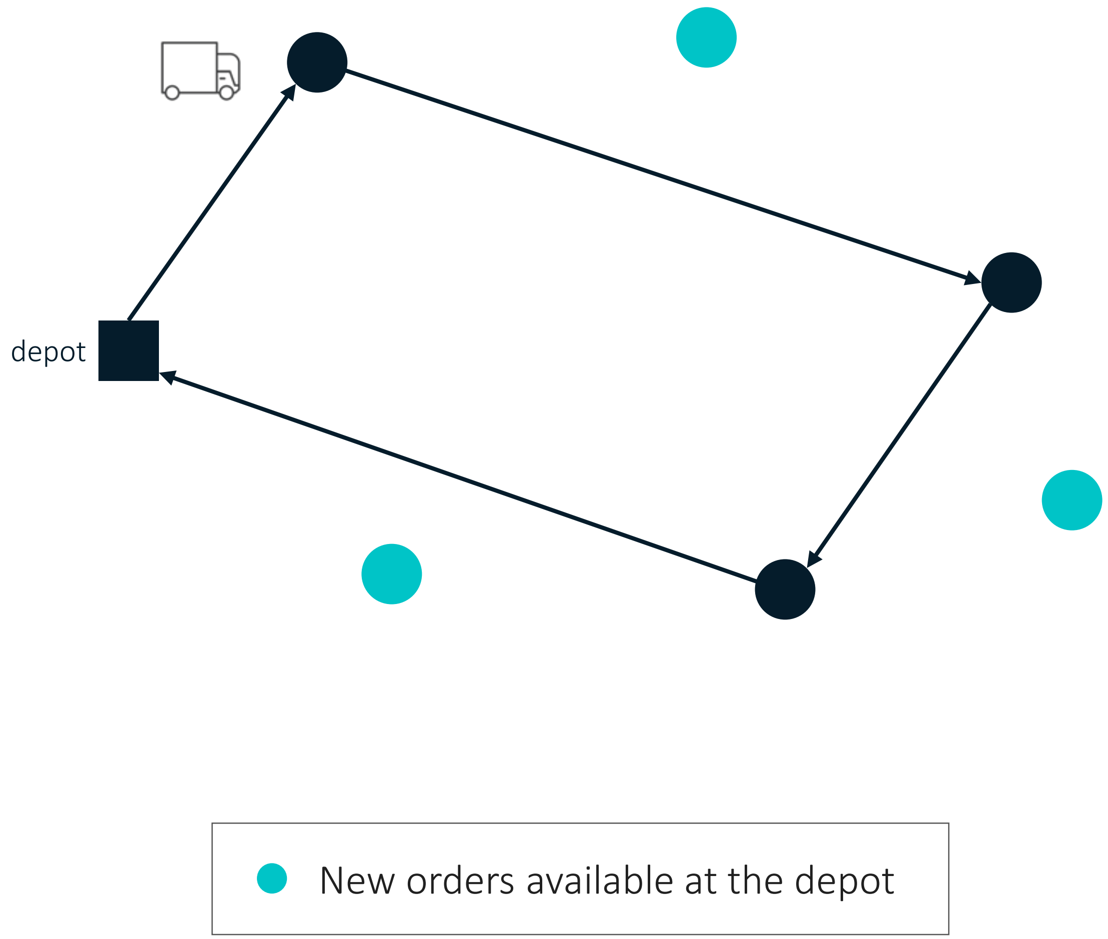
*World Economic Forum (2020). The future of the last-mile ecosystem. Technical report.

APPLICATION IN RURAL MEDICAL LOGISTICS

- Delivering orders that become available for dispatch at different times during the day
- Use drones to **resupply** dispatch vehicles while en route
- For medical applications, certain medicines or tests may not be available when the trucks leave the depot. These will be resupplied to the truck along the way as they become available
- **Customers (patients) need not interact with the drone**

HOW DOES THIS NEW DELIVERY SYSTEM WORK?

Using drones to resupply delivery vehicles with new orders while en route



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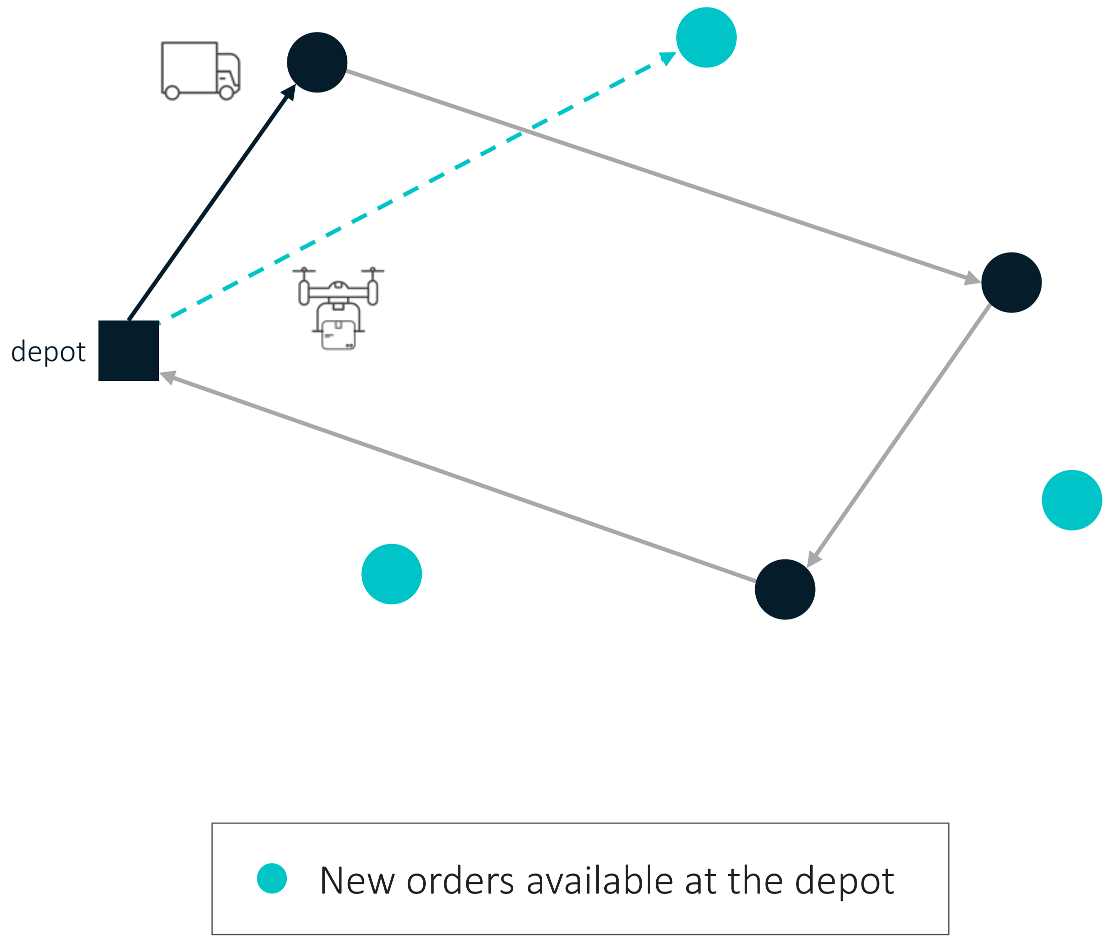

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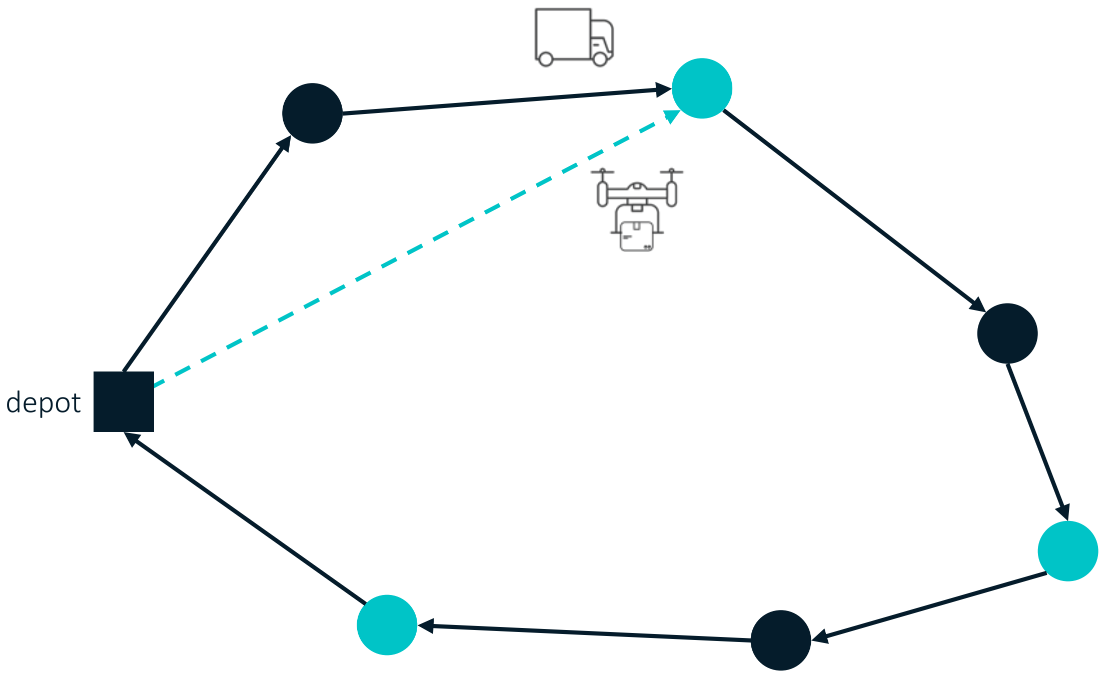


New orders available at the depot

RELEVANT LITERATURE

Traditional strategy

Instruct an en-route vehicle to **return to the depot** to collect newly released orders

Studied in both static and dynamic settings

(Archetti et al., 2018; Klapp et al., 2018; Ulmer et al., 2019)

Archetti, C., Feillet, D., Mor, A., & Speranza, M. G. (2018). An iterated local search for the traveling salesman problem with release dates and completion time minimization. *Computers & Operations Research*, 98 , 24–37.
Klapp, M. A., Erera, A. L., & Toriello, A. (2018). The dynamic dispatch waves problem for same-day delivery. *European Journal of Operational Research*, 271 (2), 519–534.
Ulmer, M. W., Thomas, B. W., & Mattfeld, D. C. (2019). Preemptive depot returns for dynamic same-day delivery. *EURO Journal on Transportation and Logistics*, 8 (4), 327–361.

Resupply strategy

Dayarian et al. (2020)

Dynamic · single truck · single drone

First to propose the use of drones for resupply

Used **only** heuristic approaches to show the benefits of drone resupply

Dienstknecht et al. (2022)

Static · single **capacitated** truck · single drone

All orders available at the beginning of the day

Experiments show that truck returns to the depot can be advantageous

Dayarian, I., Savelsbergh, M., & Clarke, J.-P. (2020). Same-day delivery with drone resupply. *Transportation Science*, 54 (1), 229–249.
Dienstknecht, M., Boysen, N., & Briskorn, D. (2022). The traveling salesman problem with drone resupply. *OR Spectrum*, 1–42.

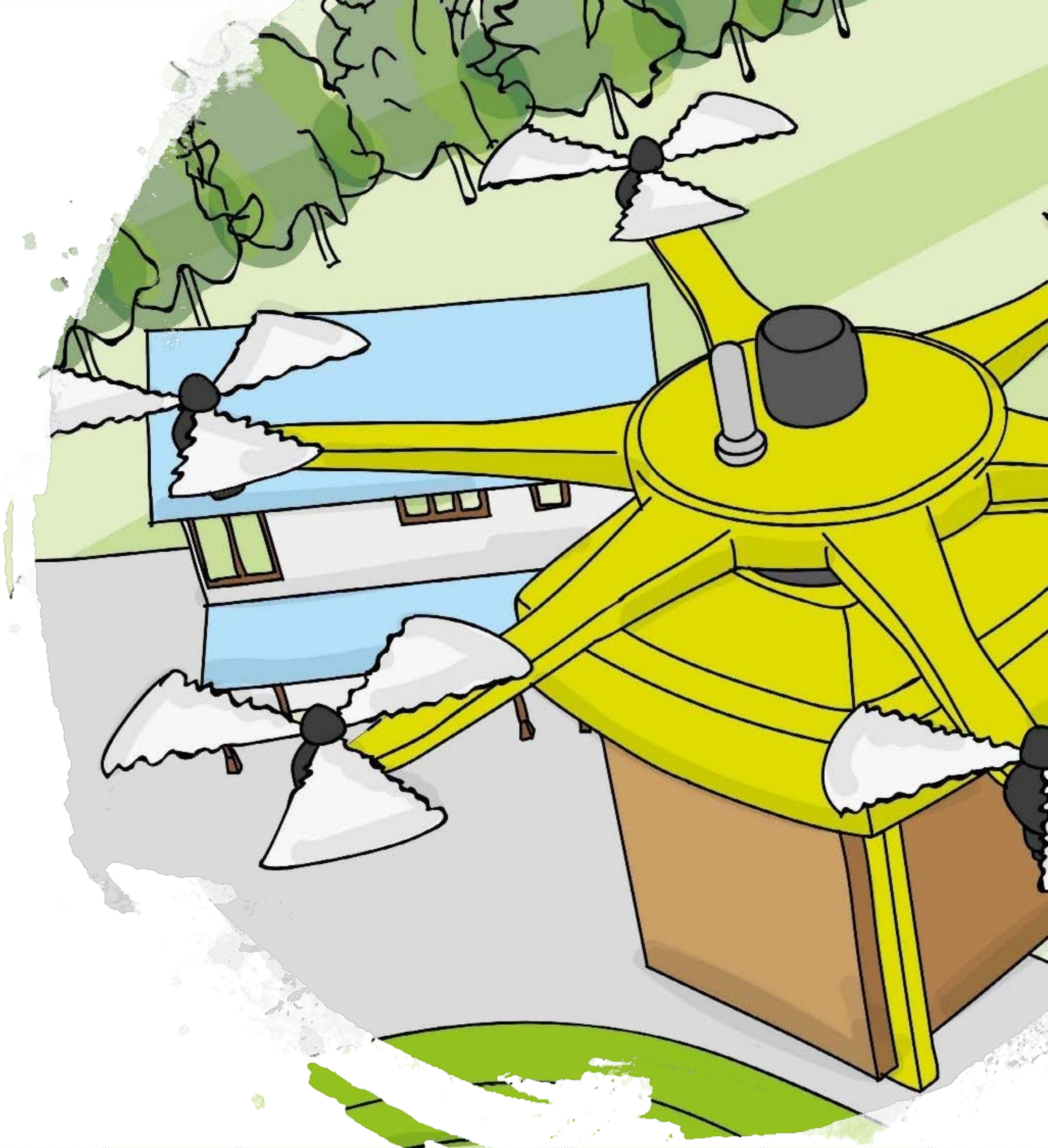
The vast majority of drone logistics literature focuses on drones for direct delivery to customers

PROBLEM DEFINITION

Find a set of routes for a fleet of trucks, synchronized with drone resupply, to deliver orders that become available for dispatch throughout the delivery horizon

ASSUMPTIONS AND CONSIDERATIONS:

- Multiple trucks and multiple drones
- Drones have a given load capacity and flight endurance
- Trucks are not capacitated
- Include fixed time to receive the drones en route
- Trucks can return to the depot
- **Deterministic and dynamic cases addressed**

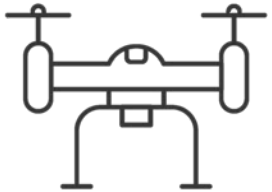


OVERVIEW OF SOLUTION APPROACHES

We leveraged the problem's decision structures to develop effective and computationally efficient decomposition-based heuristic approaches for solving realistic-sized instances

Routing subproblem

Define a **delivery route for each truck** without considering drone resupply or depot returns



Loading subproblem

Define optimal **drone resupply** and **truck depot return** operations for a given routing solution

INSTANCE GENERATION

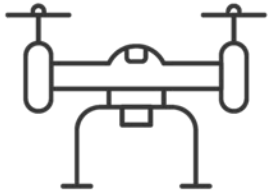
- Programmed in Java and use of CPLEX 12.8 for solving MILP models
- All orders are the same size, shape, and weight (i.e., interchangeable regarding being carried by the drone)
- **Truck:** Speed of 30 km/hr and Manhattan distances
- **Drone:** Speed of 60 km/hr and Euclidean distances
- **Drone:** Flight endurance of 45 minutes and varying load capacity (Q)
- **Release Dates:** Uniformly distributed in time between $[0, \beta * z_{TSP}]$
    - β is a multiplicative factor that defines the spread of release dates (times)
    - z_{TSP} is the time to do a TSP route visiting all the customers (ignoring release dates)
- **Degree of Dynamism (DOD):** Percentage of orders that are dynamic (arrive randomly over the day)

DETERMINISTIC, SINGLE-TRUCK, SINGLE-DRONE

SEQUENTIAL APPROACH FOR DETERMINISTIC, SINGLE-TRUCK, SINGLE DRONE VERSION

1 TSP WITH TIME WINDOWS

- Hypothetical situation where there exist as many drones as customers
- The problem collapses to a TSPTW
- The time when each customer's time window starts is given by its order's release time plus the drone flying time from the depot

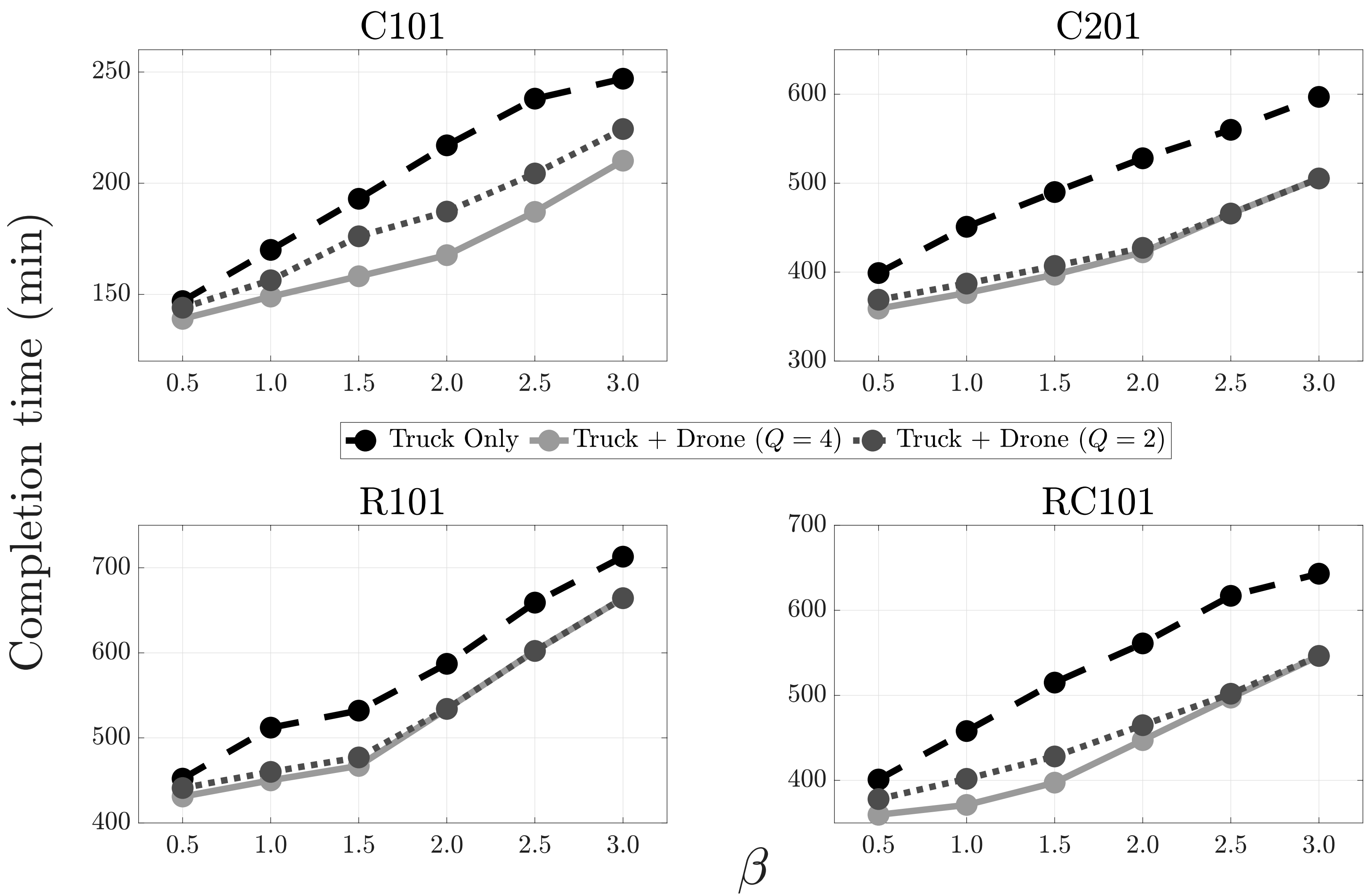


2 DRONE MODEL

- Find the best locations to resupply the truck from a single drone
- Results in a feasible solution to the original problem
- Drone routing solved through a MILP model

Objective: Minimize the completion time of the entire delivery process

TOTAL TIME – Solomon instances of 10 customers



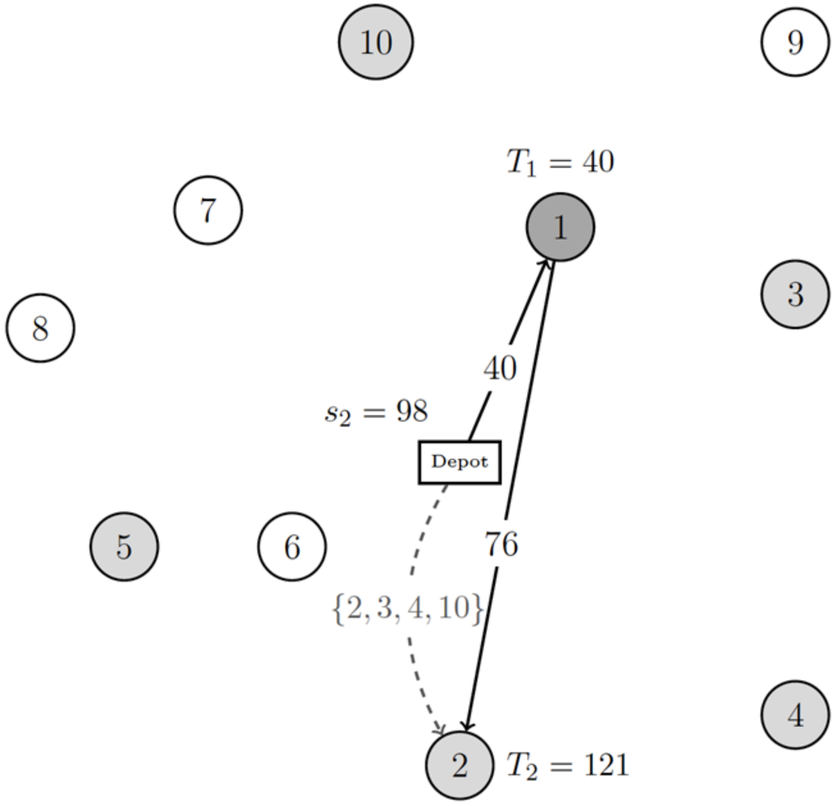
Comparison with the truck-only delivery system proposed by Archetti, C., Feillet, D., Mor, A., & Speranza, M. G. (2018). An iterated local search for the traveling salesman problem with release dates and completion time minimization. *Computers & Operations Research*, 98, 24-37. **C** instances are clustered – **R** instances are random.

10 CUSTOMERS

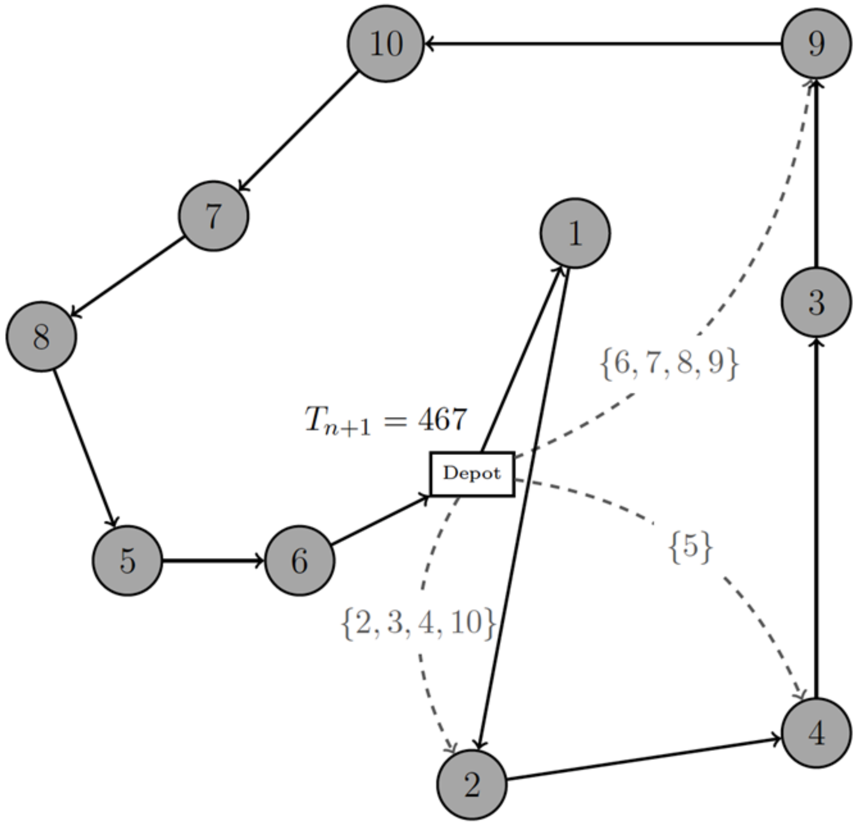
CAPACITY: 2 or 4

$\beta \in [0.5, 3.0]$

TYPICAL SOLUTION



First drone resupply operation



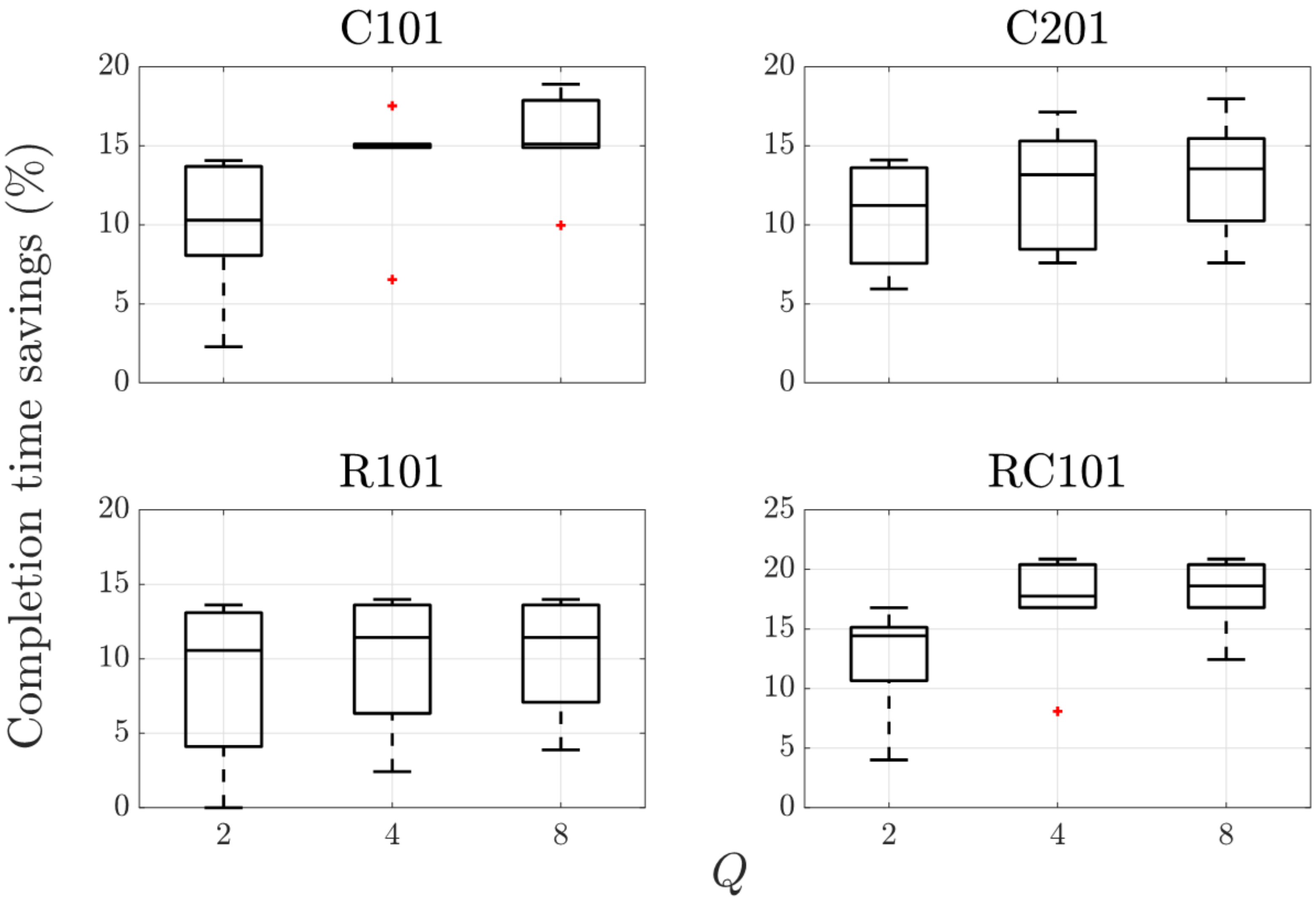
Optimal solution

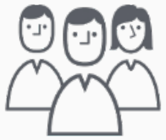
10 CUSTOMERS

CAPACITY: 4

$\beta \in [0.5, 3.0]$

TOTAL TIME – Solomon instances of 15 customers





15 CUSTOMERS

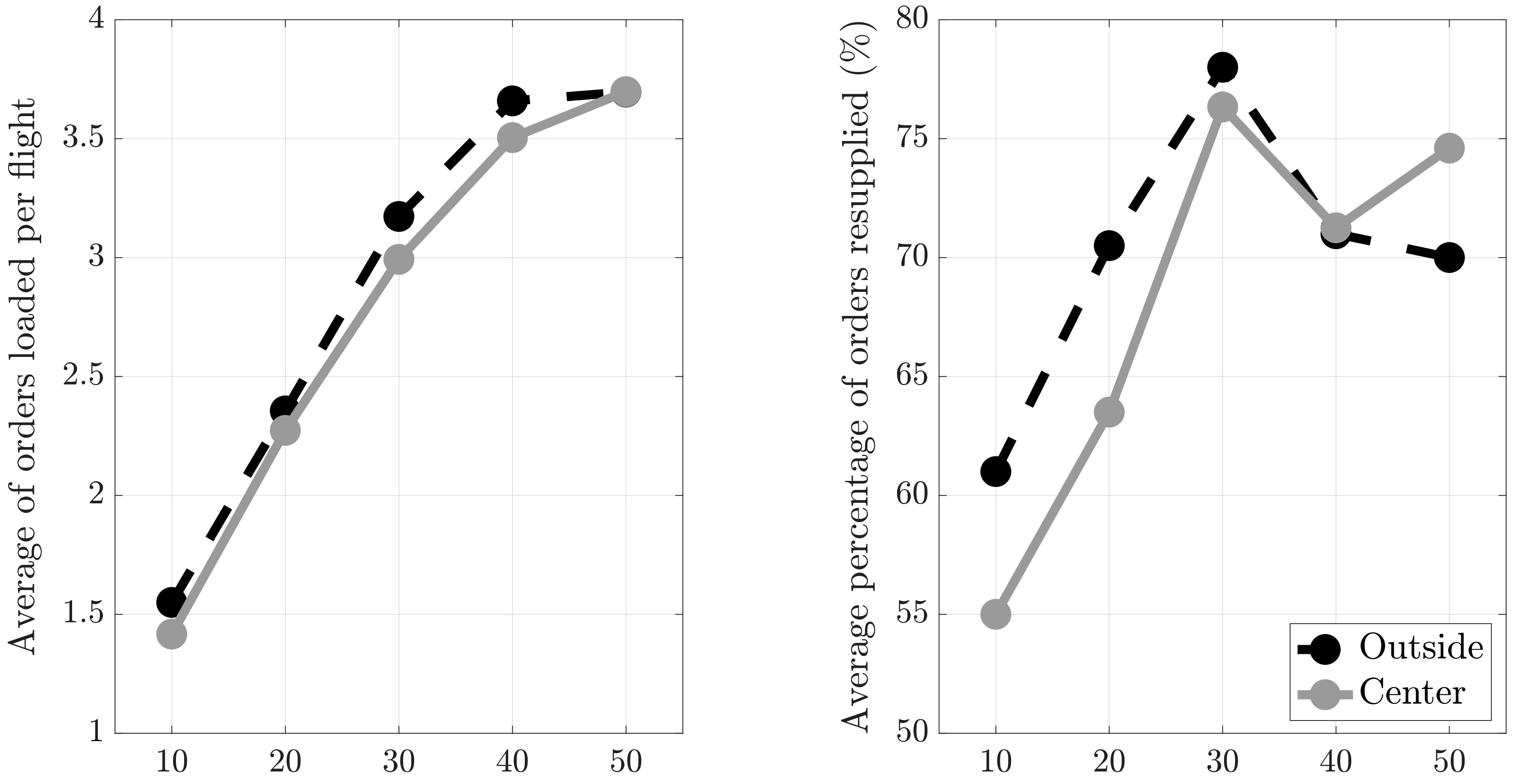
CAPACITY: 2,4,8

$\beta \in [0.5, 3.0]$

*Solomon, M. M. (1987). Algorithms for the vehicle routing and scheduling problems with time window constraints. *Operations Research*, 35 (2), 254–265.

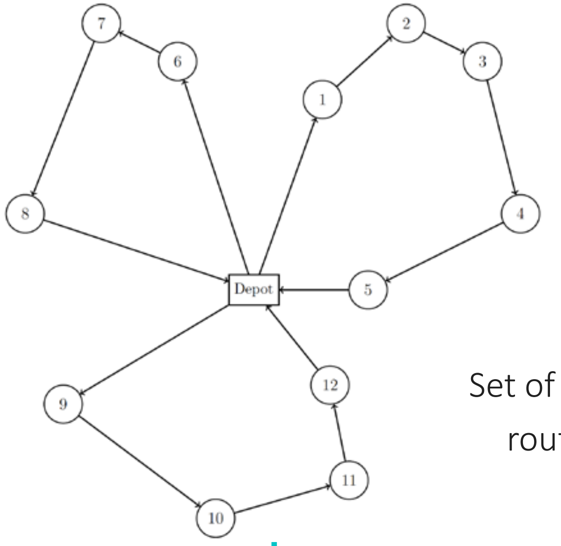
UTILIZATION OF THE DRONE

Uniform random customers with two possible depot locations and drone capacity of four



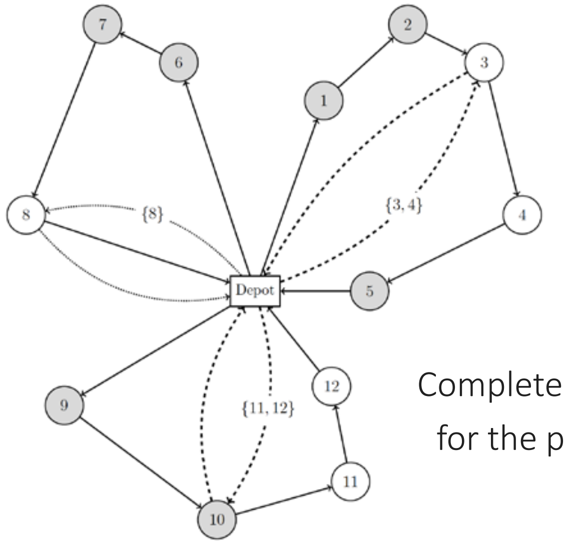
DETERMINISTIC, MULTI-TRUCKS, MULTI-DRONES

ITERATIVE APPROACH FOR DETERMINISTIC, MULTI-TRUCKS, MULTI-DRONES VERSION



Set of truck routes

↓ DRONE MODEL



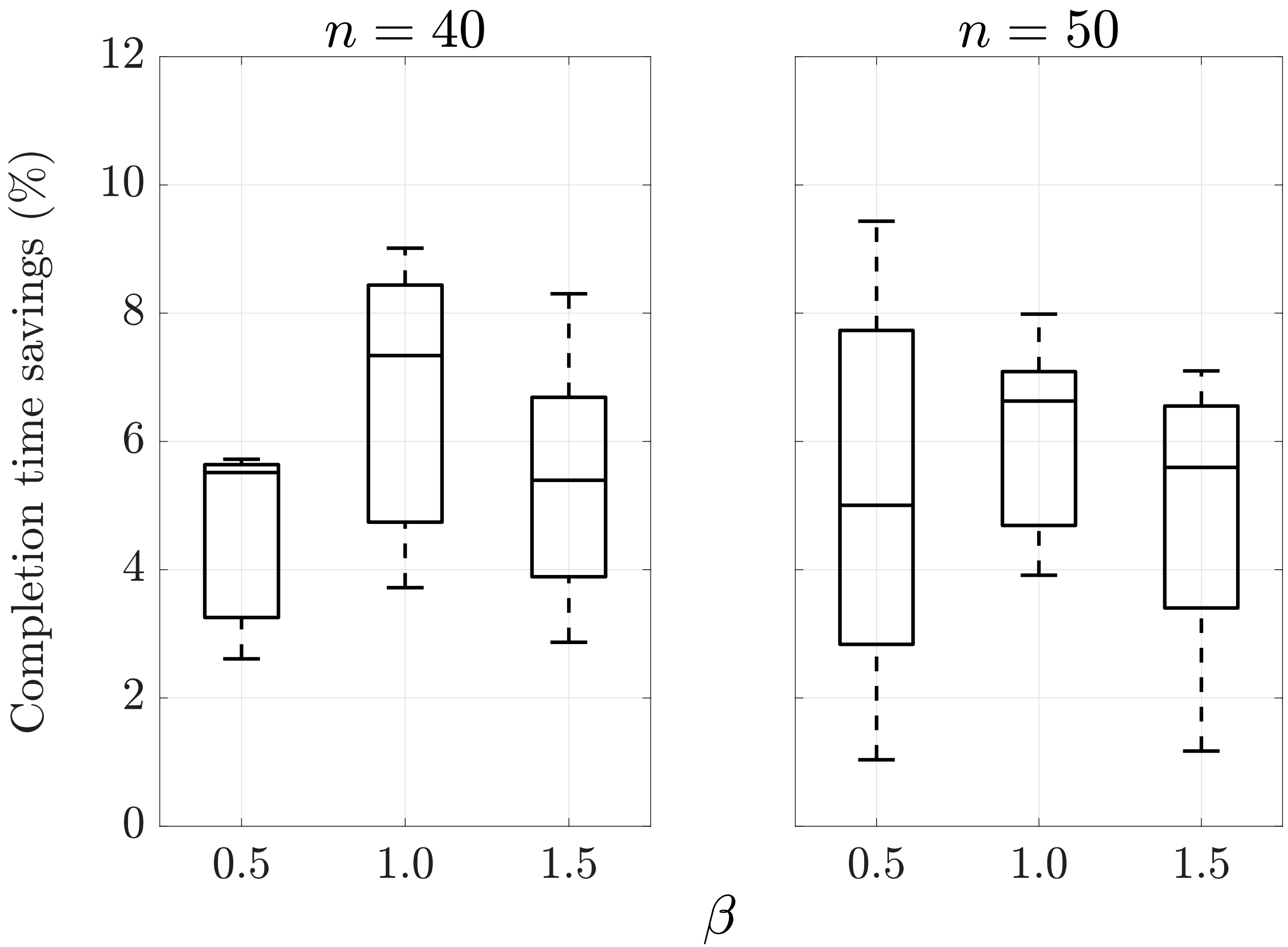
Complete solution for the problem

- **Tabu search approach**: Truck routes are iteratively modified using initial solution constructed by I1 Heuristic by Solomon*
- **Drone model MILP** quickly finds optimal loading operations (drone resupply and depot returns) for given set of truck routes
- Use two **pruning strategies** to solve the drone model *only* for promising sets of truck routes
- **Outperforms state-of-the-art solvers** for instances of 15 customers or more

*Solomon, M. M. (1987). Algorithms for the vehicle routing and scheduling problems with time window constraints. *Operations Research*, 35 (2), 254–265.

Objective: Minimize the completion time of the entire delivery process

COMPLETION TIME SAVINGS



Savings derived from drone resupply are likely concave with respect to the spread of order release times

Two trucks and two drones with capacity of 10 orders each.

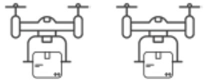
FLEET UTILIZATION

β	Truck-and-drone				Truck-only	
	Total drone sorties	Orders shipped per sortie	Total truck returns	Orders collected per return	Total truck returns	Orders collected per return
0.5	6.7	6.8	0.4	5.8	6.7	6.5
1.0	9.4	4.4	2.3	2.7	9.7	4.7
1.5	12.7	3.3	2.8	1.7	11.1	3.7

Average fleet utilization for 10 instances. Maximum run-time of **one hour**.

- Trucks still return to the depot.
- Trucks returning to the depot can reduce truck waiting times for drones.

50 customers



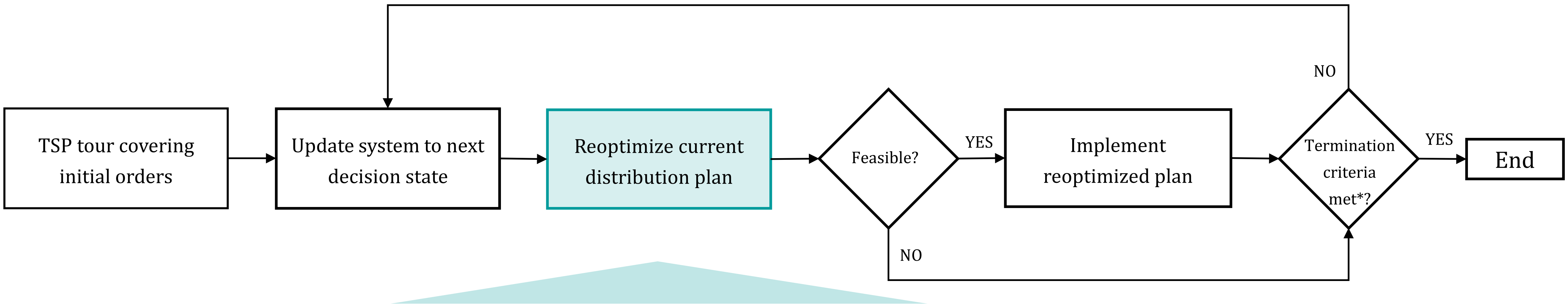
Two drones with capacity of 10 orders each

Two trucks

DYNAMIC, SINGLE-TRUCK, MULTI-DRONES

REOPTIMIZATION APPROACH FOR DYNAMIC, SINGLE-TRUCK, MULTI-DRONES VERSION

Objective: Maximize the total number of orders delivered within an operational horizon



- The new order is inserted into the truck tour using cheapest insertion
- The **Drone Model MILP** is then solved to find optimal resupply operations to dispatch all orders available at the depot

*The termination criterion for the reoptimization is either when the time budget is zero (the truck cannot accommodate more orders) or when the last order arrives.

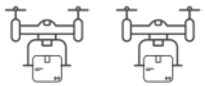
PERFECT-INFORMATION GAP

We adapted instances from Archetti et al. (2018).

Customers	DOD (%)	Perfect Information	Reoptimization	
		Fill rate (%)	Fill rate (%)	Gap (%)
10	25	92.0	80.0	12.7
	50	88.0	77.0	12.1
	75	81.1	64.4	20.2
15	25	92.0	86.7	5.7
	50	86.7	78.0	10.0
	75	79.3	65.3	17.6
20	25	93.5	83.5	10.6
	50	89.0	76.5	14.0
	75	80.0	68.0	17.1

Average of 10 instances, using the **R101 customer distribution** (randomly distributed customers).

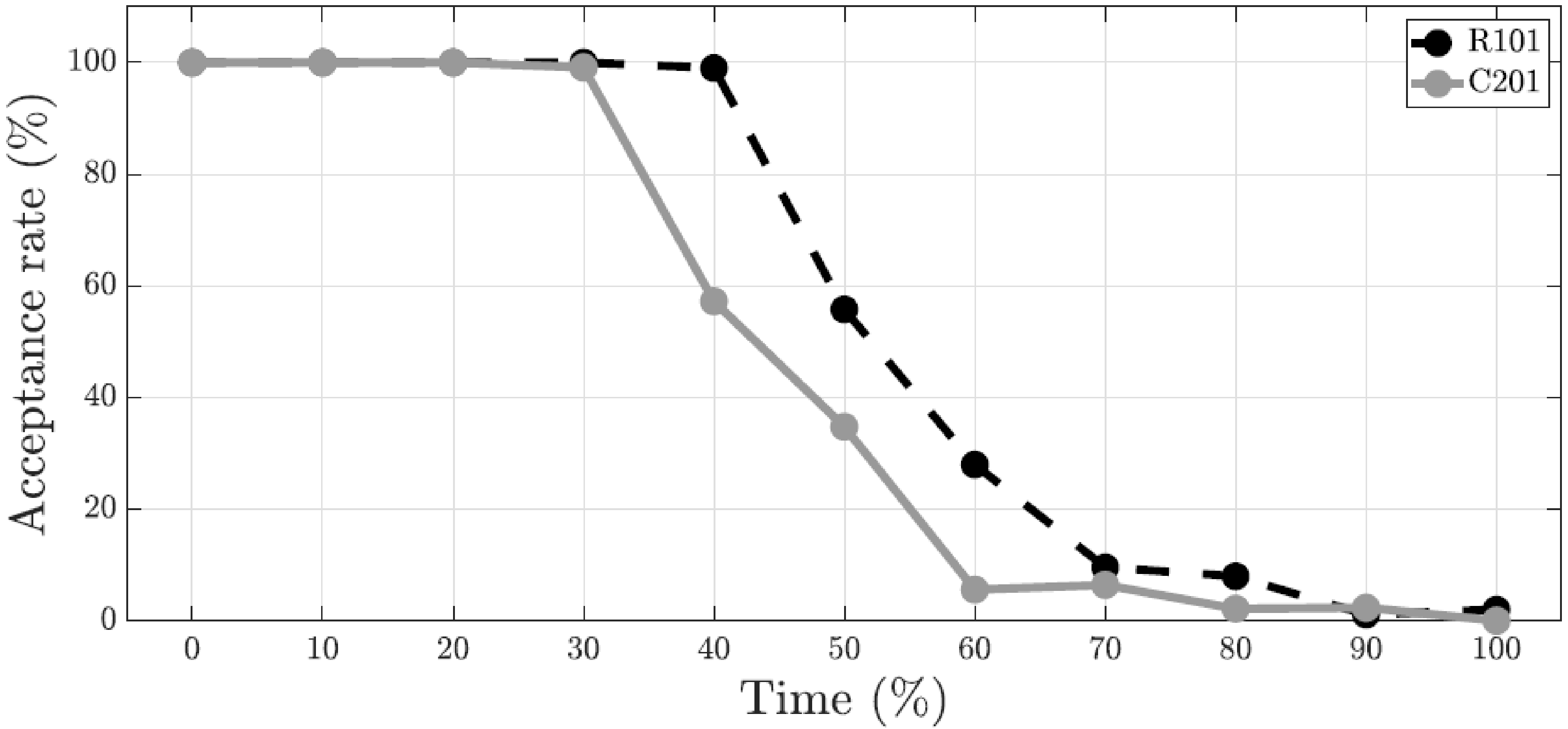
10 to 20 customers



Two drones with capacity of four orders each

DOD ∈ {25, 50, 75}

100-CUSTOMER INSTANCES = 75% DOD



Acceptance rate (%) of dynamic orders over the percentage of the delivery horizon that has elapsed.

Mean of 10 instances with two drones with a load capacity of four orders each.

100 customers

R101 and C201 distributions

DOD = 75%

100-CUSTOMER INSTANCES – 75% DOD

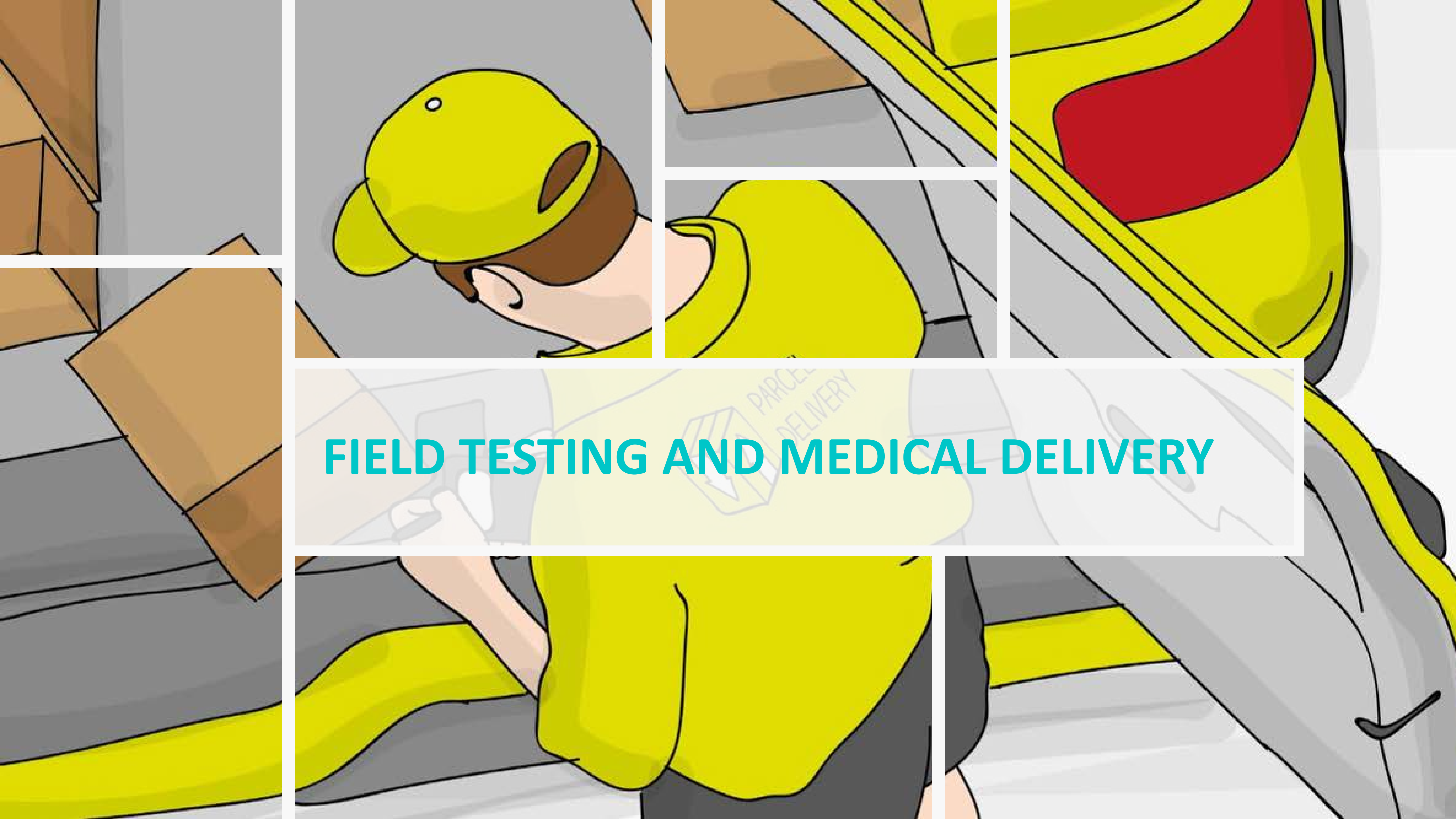
Metric	Horizon		
	Baseline	×1.25	×1.50
Fill rate (%)	66.4	82.4	97.3
Total drone sorties	13.7	18.1	20.0
Orders shipped per sortie	3.0	3.2	3.6
Idle time (%)	2.2	2.1	2.8

Average of 10 instances, considering two drones with a load capacity of four orders each. Idle time is the waiting time of the trucks. The drone sorties are timed to arrive exactly so drones do not wait. Baseline is the TSP tour time.

100 customers

R101 and C201 distributions

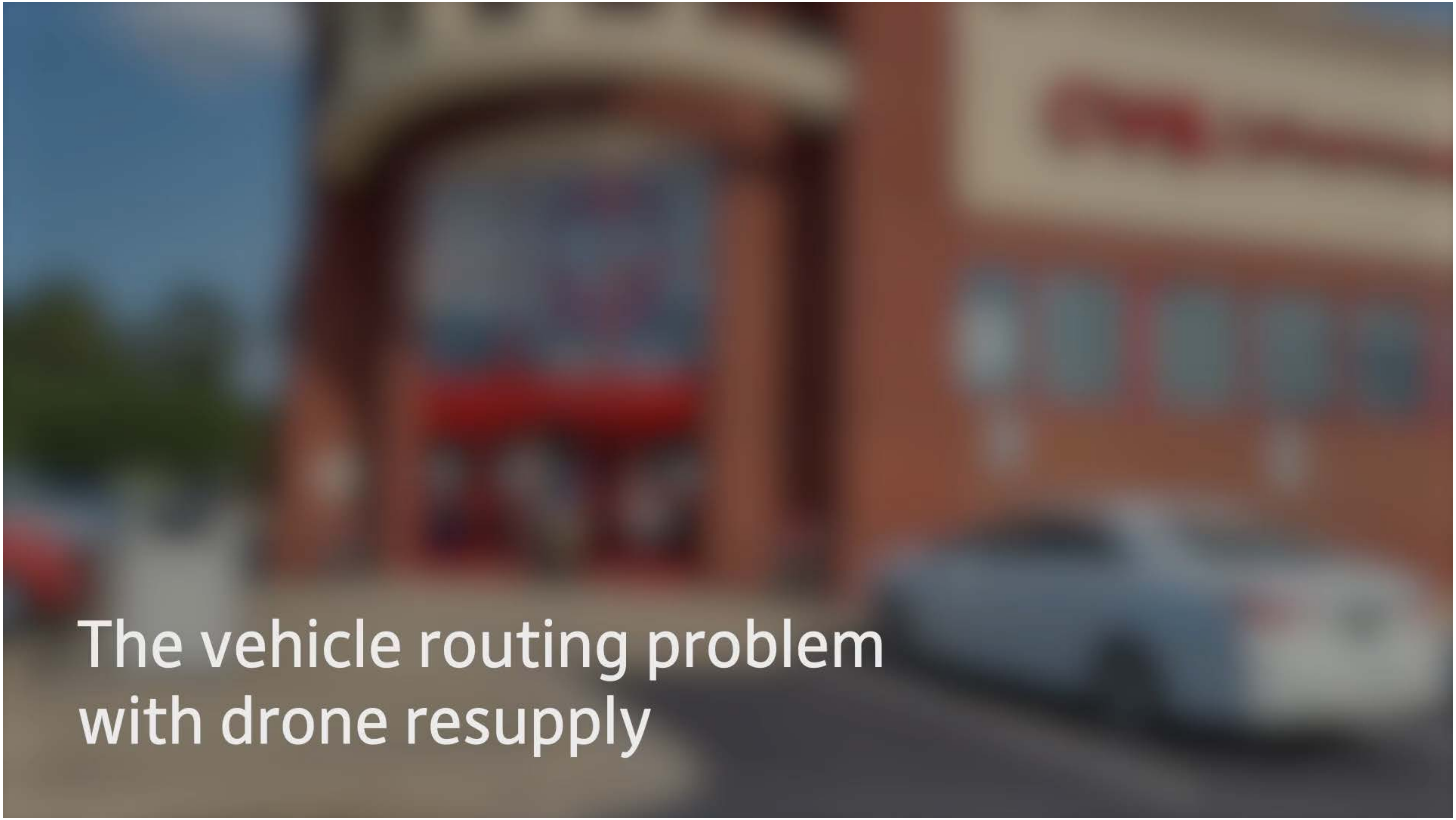
DOD = 75%



FIELD TESTING AND MEDICAL DELIVERY

FIELD TESTING

- Field testing is important to understand what assumptions are realistic
- Can also help understand model's limitations in a real-world setting
- We have two drones and have conducted proof of concept field tests
- This is our Tarot drone - which is big and strong enough for payloads
- Flies autonomously with preprogramed flight plans and has basic flight intelligence



The vehicle routing problem with drone resupply

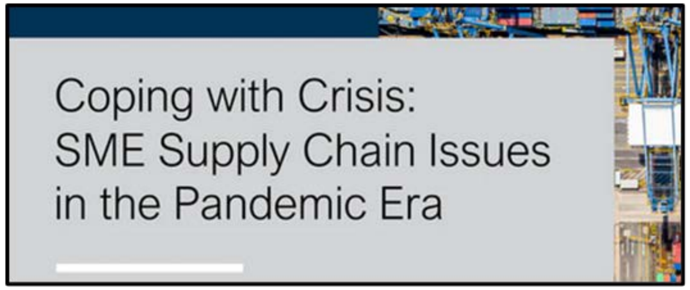
DRONES FOR MATERIAL HANDLING IN PRODUCTION

- Recent events have shown that our logistics chain is fragile and that current technology is not enough to keep up with increasing demand.
- Manufacturing is a key component of most logistics chains.
- Material handling can be a significant bottleneck, especially for small to medium-sized enterprises.
- Can the use of Uncrewed Aerial Vehicles (UAVs) provide a viable tool to support material handling activities in manufacturing processes?

Source: Global Capitalist 2021

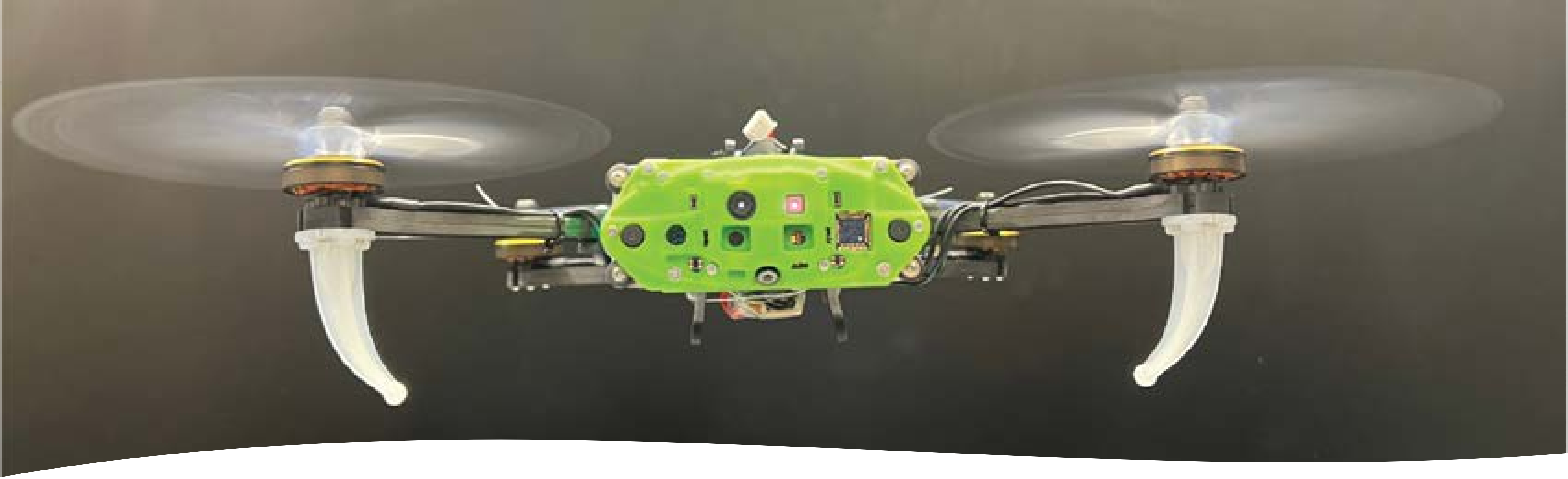
Source: McKinsey 2021

Source: CES 2021



WHY DRONES?

- In production environments, space is at a premium.
- Most automated material handling systems are large and/or require specialized layouts.
- Human-based systems require aisles and have additional safety requirements, some affecting throughput (weight, walking speed).
- Drones can fly using the fastest route possible and can do so at high speeds.
- Drones can utilize 3D space efficiently and without requiring significant investment. For new or existing facilities, drones only need the empty space above to fly through. This eliminates costly floorspace investments.
- Indoor positioning technology has seen strong development. (Computer vision, ultra-wideband, visual odometry, LIDAR.)
- Automation and drone flexibility align with Industry 5.0 and smart manufacturing principles.



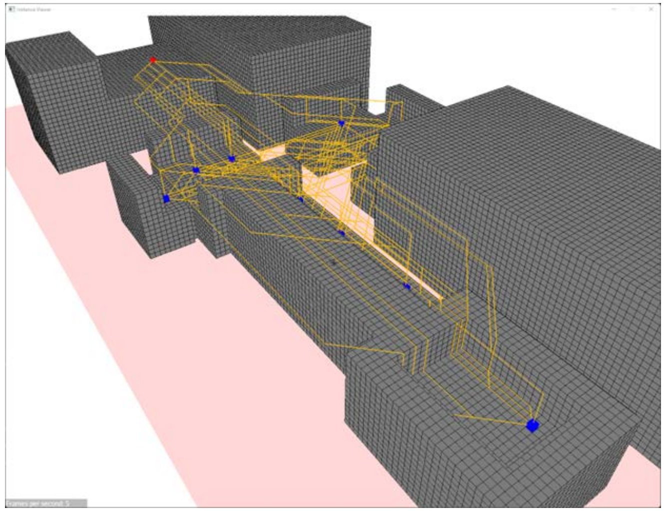
WHAT IS MISSING?

- Models and algorithms optimized for 3D air-based movement.
- This includes routing and scheduling models.
- Real-time heuristics for route planning and scheduling.
- Grasping and carrying mechanisms.
- Integration with production systems.

Phase I
Virtual
Experimentation

Mathematical Models and Heuristics

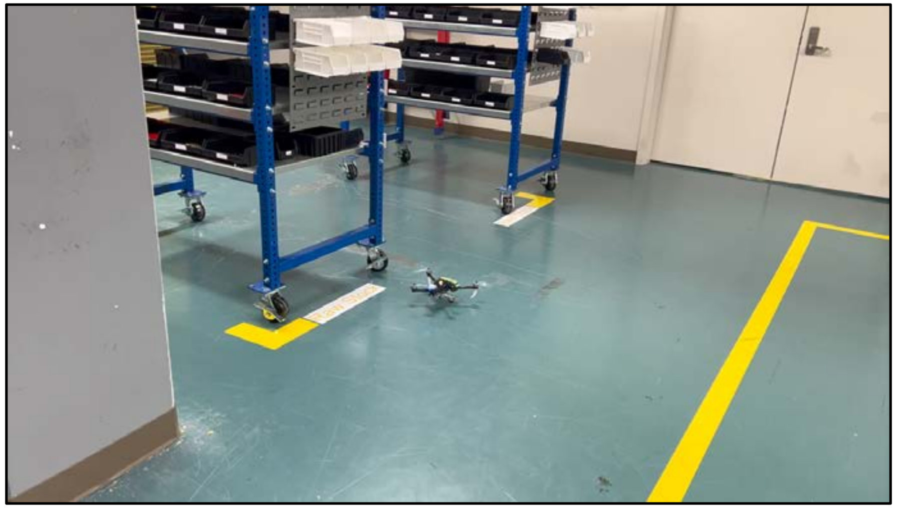
Virtual Trials on Simulation Environment



Phase II
Physical
Experimentation

Drone Outfitting

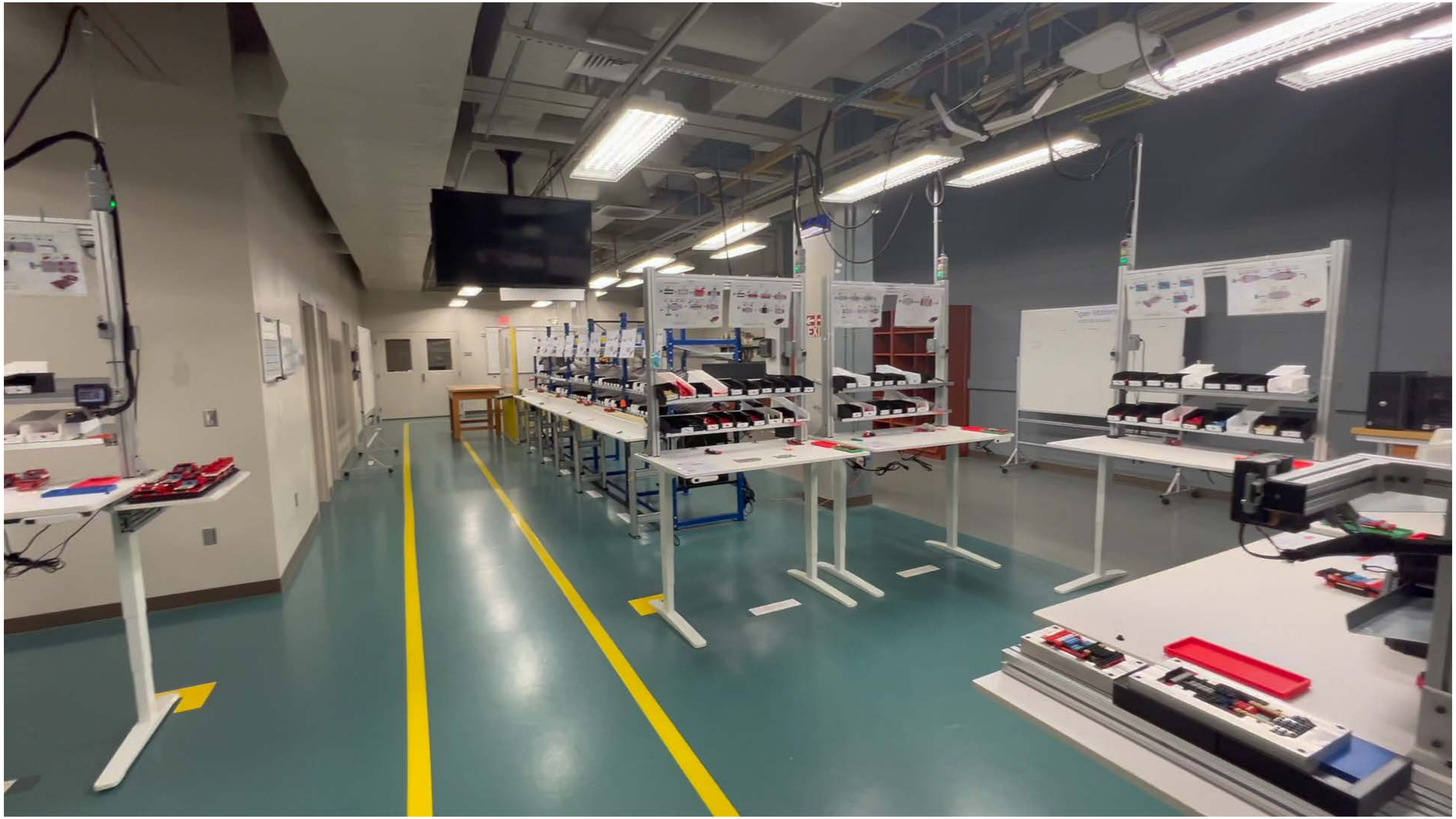
Physical Trials at Tiger Motors Laboratory



RESEARCH OVERVIEW

BUILDING THE COORDINATE SYSTEM

- Takes a definition of the room's dimensions and cuboid-shaped obstacles as input.
- Models the drone as a particle.
- Considers a safety distance, achieved by "growing" walls and obstacles by the specified amount.
- Allows for separate vertical and horizontal speeds. After the network is generated, the shortest paths between delivery points and the depot are obtained.
- Simulation model developed using Simio.
- Can generate orders dynamically or from an order list.
- Uses the network generated by the distance matrix generation process.



EQUIPMENT ASPECTS

- GPS-less environments (indoor) require the use of specialized drones.

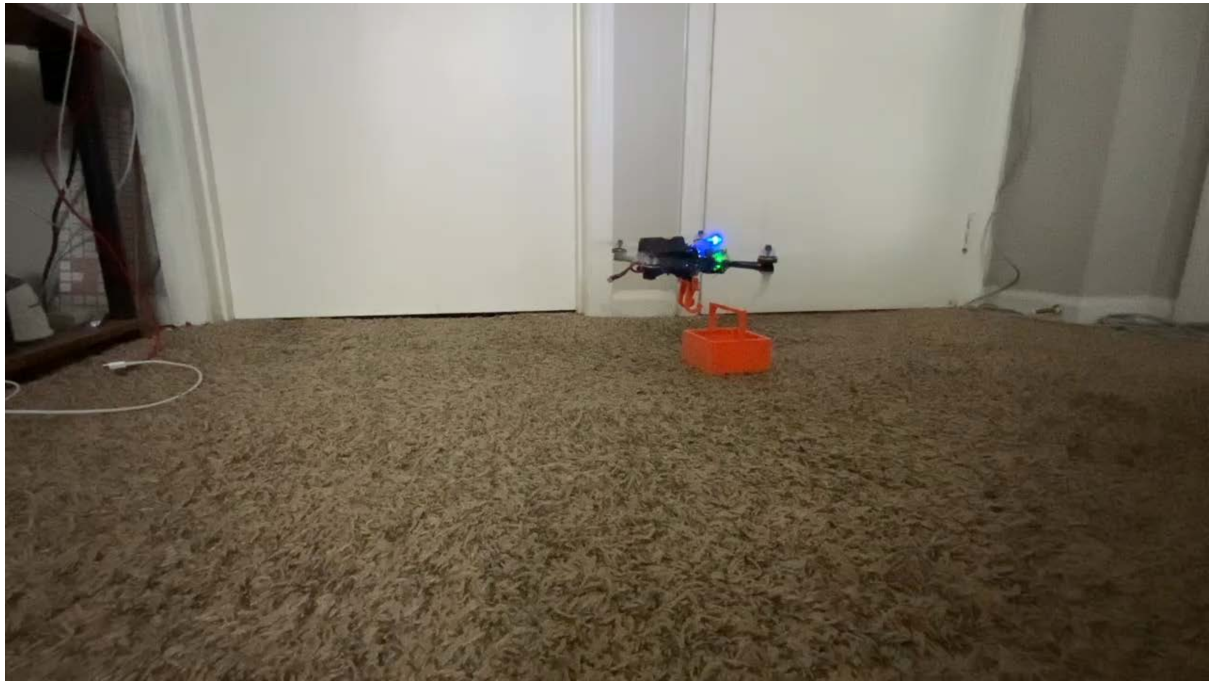
- The indoor environment imposes strict limitations on the size of the UAV.

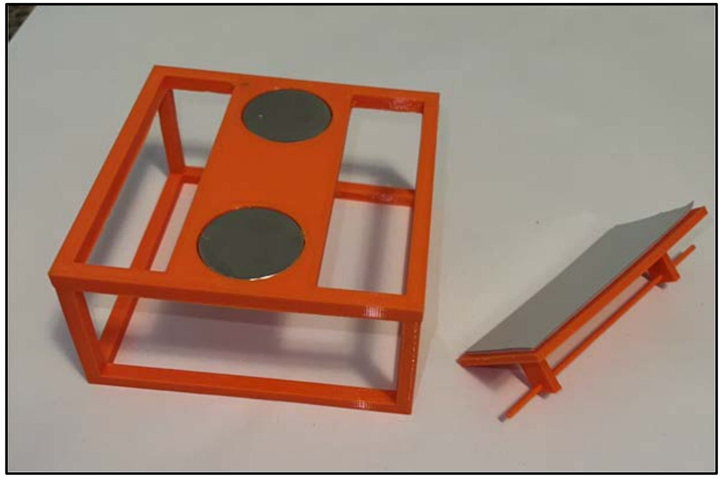
- We purchased two indoor drones with SLAM (simultaneous localization and mapping) capabilities from ModalAI, the Seeker (small) and the Sentinel (large). They work with machine vision to navigate.

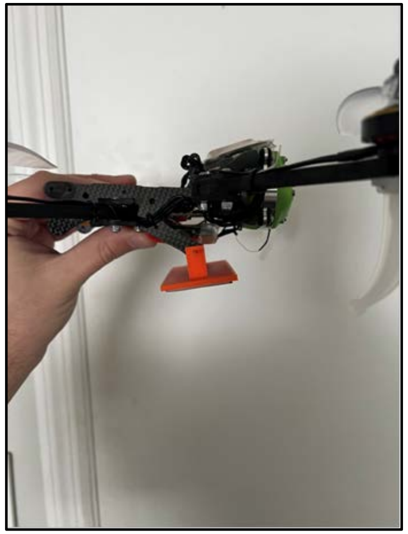
- We have also acquired an external indoor positioning system made by Pozyx, a Belgium company.

GRASPING AND TRANSPORT MECHANISM

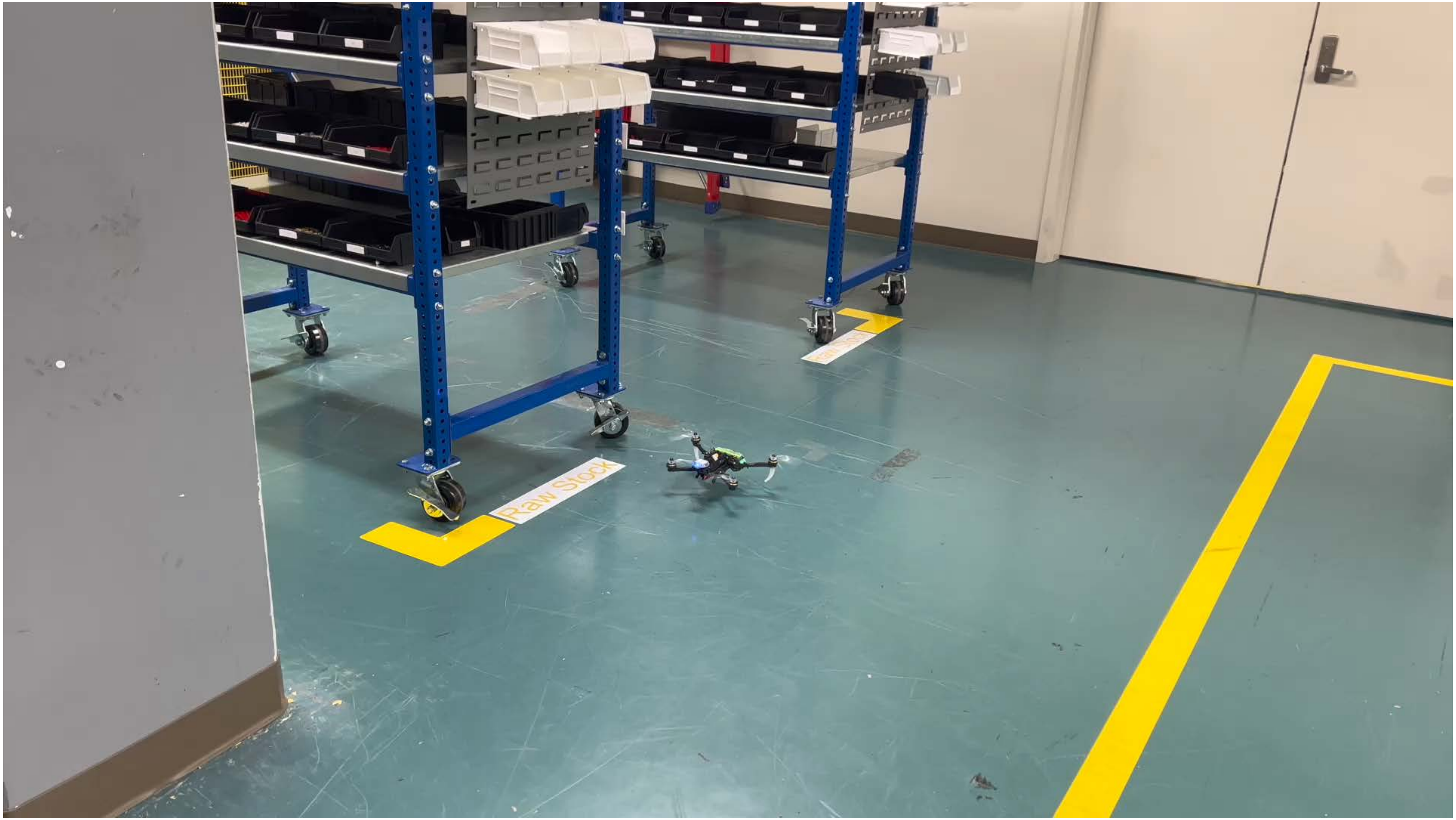
- For our initial physical experiments, some human or robotic assistance for the payload / order preparation will likely be needed.
- We are using 3D printing to create our prototypes, as well as Arduino boards, for the pickup and drop-off mechanism.
- This will be integrated with the drone's software so it can be autonomously controlled.
- Using magnets to pick up and release the parts in their carrying container after unsuccessful trial with hooks







SMALL DRONE IN INITIAL APPLICATION PRODUCTION AREA



MATHEMATICAL MODEL – SOLVED WITH GUROBI

Sets

$N: set\ of\ nodes$
$A: set\ of\ arcs$

Parameters

$s_i: service\ time\ at\ node\ i\ (drop\ off)$
$t_{ij}: travel\ time\ for\ arc\ (i,j)$
$(a_i, b_i): time\ window\ for\ node\ i$
$d_i: demand\ at\ node\ i$
$C: drone\ capacity$
$K: maximum\ number\ of\ routes$
$I: maximum\ idle\ time\ in\ between\ nodes$

Decision Variables

$$x_{ijk}: \begin{cases} 1 \ \ if\ route\ k\ uses\ arc\ i,j \\ \qquad 0\ otherwise \end{cases}$$

$w_{ik}: start\ of\ delivery\ (drop\ off) for\ node\ i\ on\ route\ k$

$$z_{ik}: \begin{cases} w_{ik} \ \ if\ i\ is\ the\ first\ node\ of\ route\ k \\ 0\ otherwise \end{cases}$$

MATHEMATICAL MODEL

$$\min \sum_{k\in K} t_{ij}x_{ijk} \quad (1)$$

$$\sum_{k\in K}\sum_{i\in N\setminus\{0,j\}} x_{ijk} = 1 \qquad \forall\, i\ \in N \setminus \{0, n+1\}\ (2)$$

$$\sum_{j\in N\setminus\{0\}} x_{0jk} = 1 \qquad \forall\, k \in K\ (3)$$

$$\sum_{i\in N\setminus\{n+1\}} x_{ijk} - \sum_{i\in N\setminus\{0\}} x_{jik} = 0 \qquad \forall\, k\ \in K, j\ \in N\ (4)$$

$$\sum_{i\in N\setminus\{n+1\}} x_{i,n+1,k} = 1 \qquad \forall\, k\ \in K\ (5)$$

$$w_{ik} + s_i + t_{ij} - w_{jk} \le \left(1 - x_{ijk}\right)M \quad \forall\, k\ \in K, (i,j) \in A\ (6)$$

$$w_{ik} + I_{MAX} + s_i + t_{ij} - w_{jk} \ge \left(x_{ijk} - 1\right)M \quad \forall\, k\ \in K, (i,j) \in A\ (7)$$

$$a_i \sum_{j\in N} x_{ijk} \le w_{ik} \le b_i \sum_{j\in N} x_{ijk} \quad \forall k \in K, i \in N\ (8)$$

$$\sum_{i\ \in N} d_i \sum_{j\in N} x_{ijk} \le C \quad \forall k\ \in K\ (9)$$

$$w_{ik} - z_{ik} \le M(1 - x_{ijk}) \quad \forall k \in K, i \in N \setminus \{0\}\ (10)$$

$$z_{ik} \le M x_{ijk} \quad \forall k \in K, i \in N \setminus \{0\}\ (11)$$

$$z_{ik} \le w_{ik} \quad \forall k \in K, i \in N \setminus \{0\}\ (12)$$

$$\sum_{i\ \in N} z_{ik} \le w_{n+1,k-1} \quad \forall k \in K (13)$$

$$x_{ijk} \in \{0,1\} \quad \forall\, k\ \in K, (i,j) \in A\, (14)$$

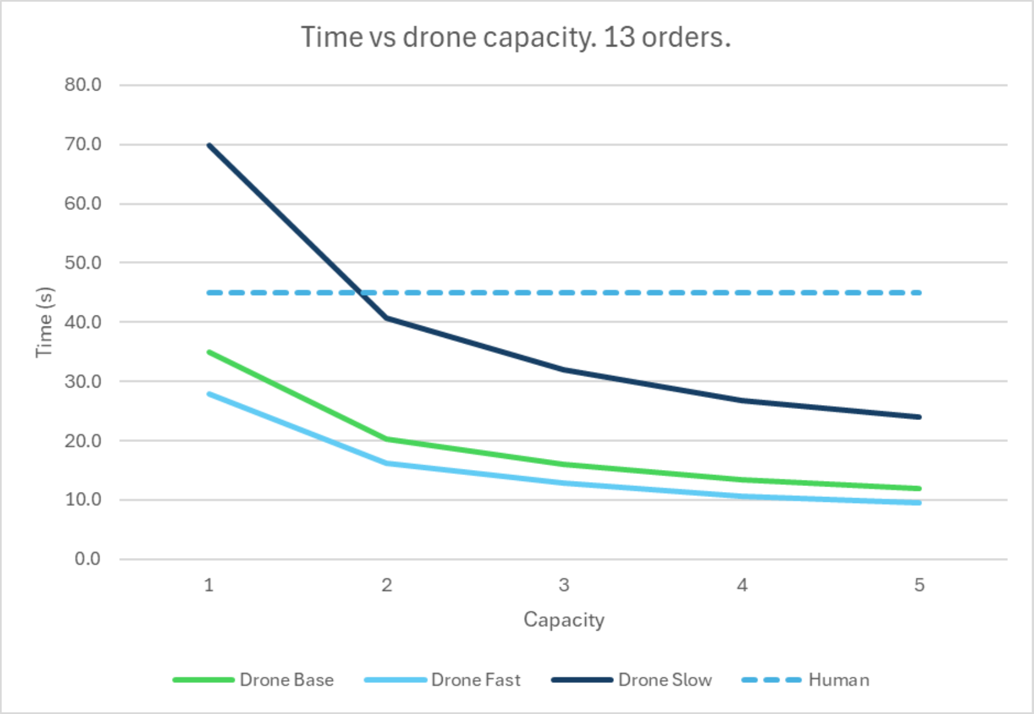
$$w_{ik} \ge 0, \qquad z_{ik} \ge 0 \quad \forall\, k\ \in K, i \in N\ (15)$$

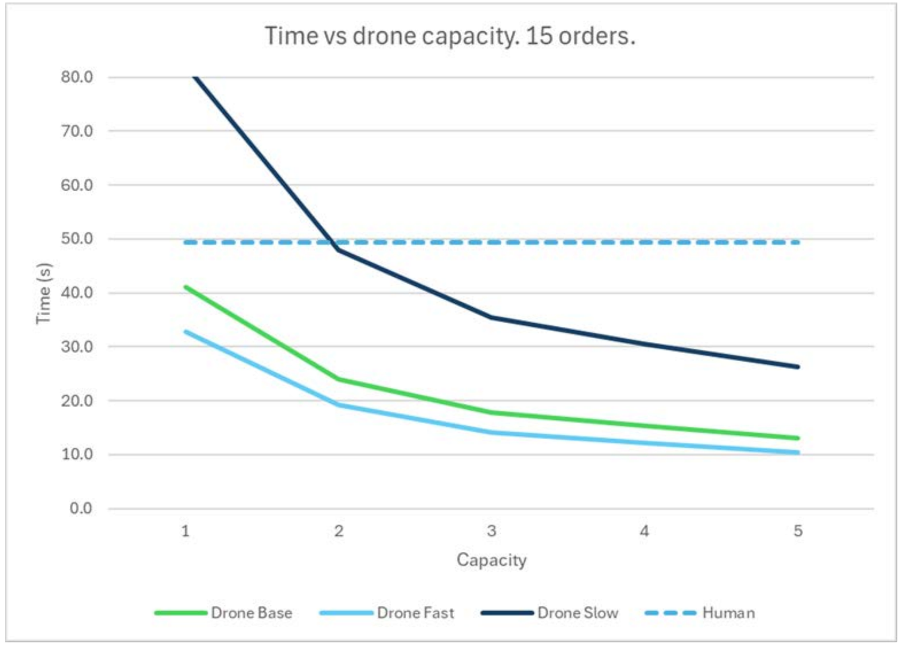
(1) Objective function. Minimizes time. (2) A node cannot be served by multiple routes (duplicate nodes). (3)-(5) Routing constraints. (6) MTZ subtour elimination constraint. (7) Maximum waiting time. (8) Time windows. (9) Drone capacity. (10) Multi trip constraint, subsequent routes must start after the previous ends. (11)-(12) Domain constraints.

PRELIMINARY RESULTS

- We can conclude that there is potential in using a drone-based material handling system.
- Both the baseline and the fastest model surpass the ground-based system. The slowest drone, is better also once capacity reaches 2.
- Even when drone capacity is quite limited, drones are able to scale easily because of their ability to use the 3D space and avoid congestion.

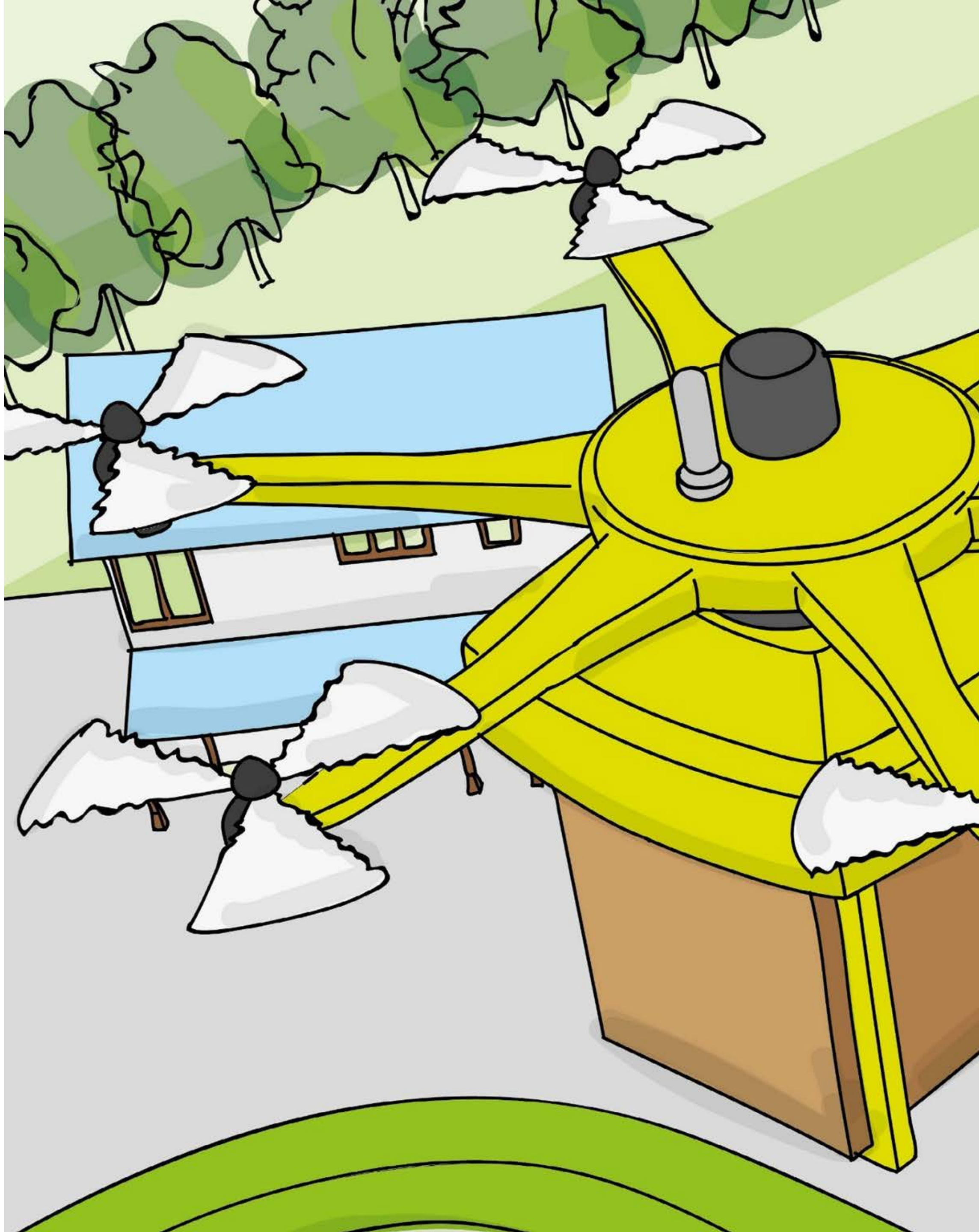
In these runs the time windows are 1 minute before and 1 minute after the scheduled time, the "service time" or delivery/drop off time, is 30 seconds, and the maximum waiting time is 1 minute.





CONCLUSIONS

- Drones do not require large investments in capital and are very flexible
- Are environmentally friendly
- Drone resupply is more pragmatic than drone delivery and can significantly reduce the total delivery time
- This is a practical method for medical delivery in rural environments as the drone and patient do not interact
- Using drones in production environments has some interesting potential benefits including better space utilization and improved throughput
- Indoor drones have challenges not experienced with outdoor drones with positioning and safety
- Offers potential to fully utilize storage space by going vertical in production environments



PUBLICATIONS and WEBSITE

“The traveling salesman problem with release dates and drone resupply,” Juan C. Pina-Pardo, Daniel F. Silva and Alice E. Smith, *Computers & Operations Research*, vol. 129, May 2021. https://doi.org/10.1016/j.cor.2020.105170

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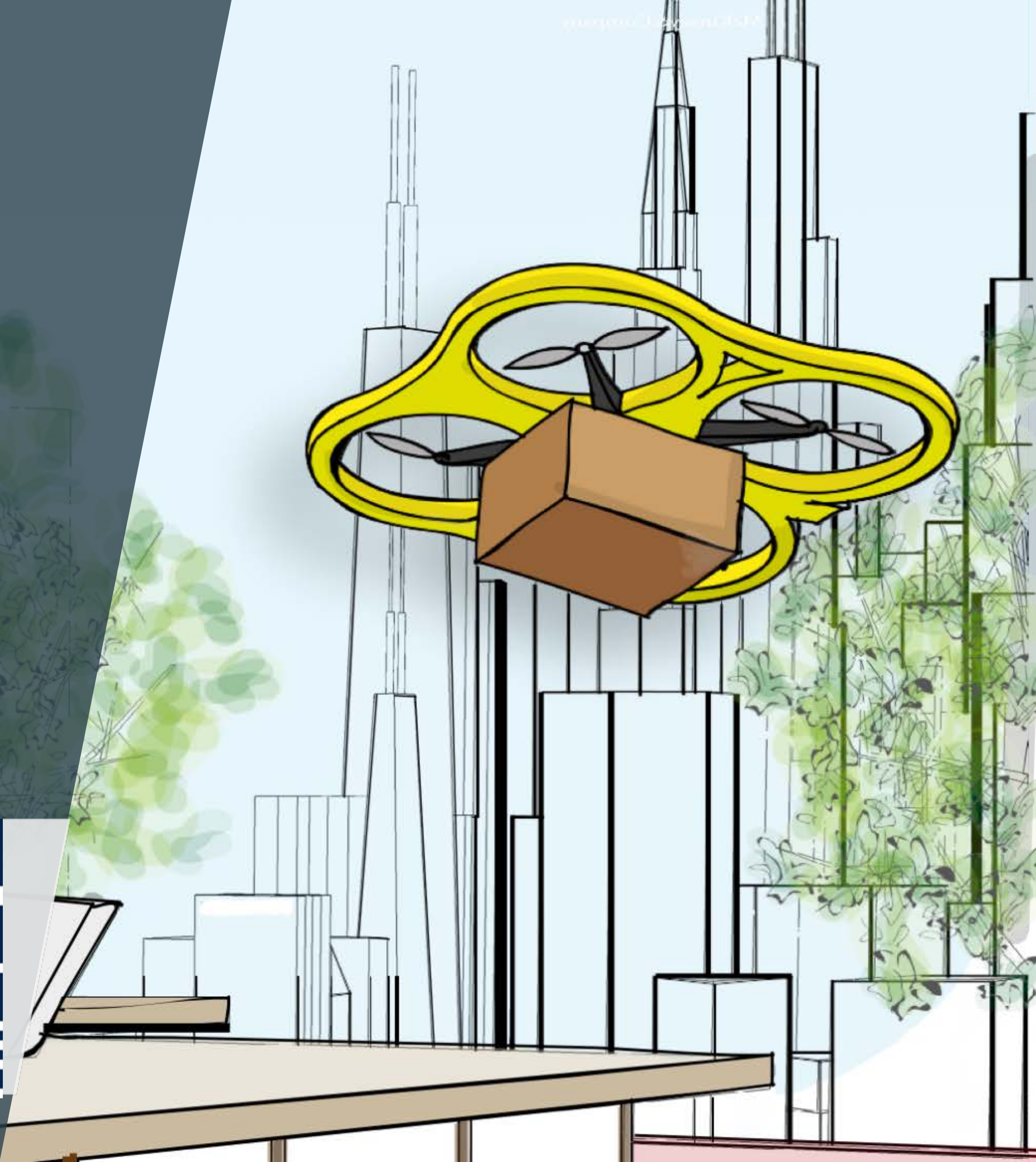

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