Innovative Strategies for Sustainable and Efficient Last-Mile Delivery

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Joint work with G. Colajanni - D. Sciacca

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PIANO NAZIONALE DI RIPRESA E RESILIENZA

ACHILLES

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- University of Naples Federico II
- Institute of System Analysis and Computer Science "Antonio Ruberti" of the National Research Council (IASI-CNR)
- University of Catania

Outline

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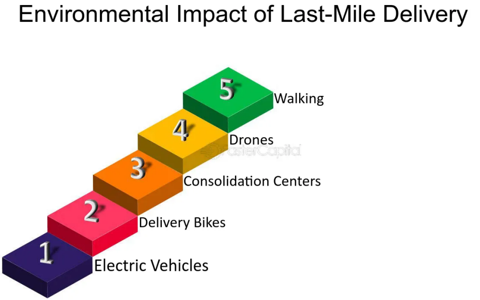
E-commerce

- The rapid growth of e-commerce has intensified the need for efficient last-mile delivery solutions

Environmental concerns

- Rise of environmental concerns and the emergence of new business models have prompted companies to explore alternative strategies to optimize last-mile delivery



Green Vehicles

- One promising approach is the integration of **green vehicles** into the last-mile delivery process (represent a good alternative to petrol and diesel-powered fleets, reduce carbon emissions and reduce operational costs)

Crowdsoursing

- Another approach is the integration of crowdsourced drivers into the last-mile delivery process

Regular Vehicles and Occasional Drivers

- We develop a model to optimize last-mile delivery operations using a combination of RVs and ODs (individuals who can transport goods as part of their daily routines). Also this approach results in significant cost reductions and increased efficiency

Parcel Lockers

- Another approach is the use of parcel lockers which eliminate the inconvenience of missed deliveries and restrictive delivery schedules.

Parcel Lockers

Advantages:

They are very useful in urban logistics and provide numerous advantages for consumers and companies.

For consumers:

- eliminate the inconvenience of missed deliveries and restrictive delivery schedules
- provide 24/7 accessibility
- reduce dependency on home delivery

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For companies, like Amazon:

- contribute to cost reduction, since multiple deliveries into a single location are allowed
- minimize failed delivery attempts
- reduce carbon emissions

Truck-drone Systems

- Another solution is the truck-drone system (which typically consists of delivery trucks which serve as mobile hubs from which drones are deployed to deliver packages to customers).

Truck-drone Systems

Advantages:

- Drones can handle short-distance deliveries (particularly in congested urban areas or remote rural locations)
- Significantly reduce total delivery times
- Significantly reduce energy consumption compared to conventional truck-only routes.

Literature Overview

1. C. Archetti, M. Savelsbergh, M.G. Speranza, *The Vehicle Routing Problem with Occasional Drivers*, European Journal of Operational Research, 254, 2016, 472-480:
   the authors examine a scenario where a company can use both its own fleet of capacitated vehicles and drivers, as well as occasional drivers who make a single delivery using their own vehicles for a small compensation, provided the delivery is near their destination. The company's goal is to minimize total delivery costs.

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   the authors examine a scenario where a company can use both its own fleet of capacitated vehicles and drivers, as well as occasional drivers who make a single delivery using their own vehicles for a small compensation, provided the delivery is near their destination. The company's goal is to minimize total delivery costs.
2. C. Archetti, F. Guerriero, G. Macrina, *The online vehicle routing problem with occasional drivers*, Computers and Operations Research, 127, 2021:
   the authors study a vehicle routing problem where customer requests are either pre-planned or arrive dynamically during distribution. The company uses a fixed fleet of vehicles, supplemented by occasional drivers. Penalties apply for time window violations or unserved requests. The goal is to minimize distribution costs.

Literature Overview

1. M. Boccia, A. Mancuso, A. Masone, C. Sterle, *Exact and heuristic approaches for the Truck-Drone Team Logistics Problem*, Transportation Research Part C: Emerging Technologies, 165, August 2024, 104691:
   the authors address the truck-and-drone routing problem, where drones can visit multiple customers per flight. They examine scenarios where the drone either lands or hovers at recollection points.

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   the authors address the truck-and-drone routing problem, where drones can visit multiple customers per flight. They examine scenarios where the drone either lands or hovers at recollection points.
2. G. Colajanni, P. Daniele, A. Nagurney, *Centralized Supply Chain Network Optimization with UAV-based last mile deliveries*, Tranportation Research Part C, 155, 2023, 104316:
   we develop a centralized supply chain network optimization model to maximize a company's total profit, using a fleet of trucks and drones for last-mile delivery. We have to take into account some realistic limitations due to drones, such as low battery capacity and limited delivery range

The Mathematical Model with Crowdsourcing

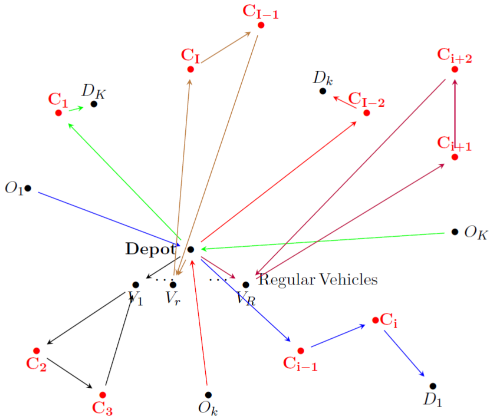

Figure: Network topology

The Mathematical Model with Crowdsoursing

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Assumptions:

1. All customers' requests have to be satisfied

The Mathematical Model with Crowdsourcing

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1. All customers' requests have to be satisfied
2. Both ODs and RVs can serve more than one customer

The Mathematical Model with Crowdsourcing

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Assumptions:

1. All customers' requests have to be satisfied
2. Both ODs and RVs can serve more than one customer
3. Both ODs and RVs can use petrol/diesel vehicles or electric vehicles

The Supply Chain Network

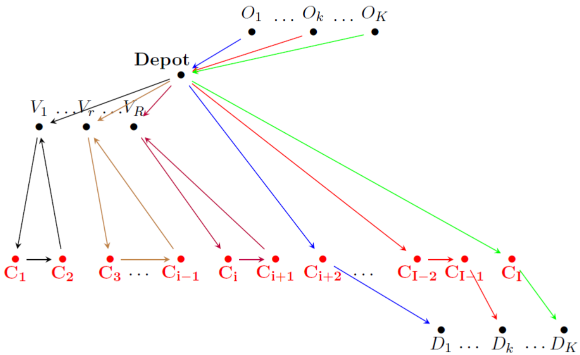

Figure: Supply chain representation

Outline

Company's behavior

Company's objective

$$\max \left\{ \sum_{i=1}^{I} \sum_{l=1}^{2} p_i^l \left[\sum_{r=1}^{R} x_{ri}^l + \sum_{k=1}^{K} y_{ki}^l \right] + N \sum_{i=1}^{I} \left[\sum_{r=1}^{R} x_{ri}^2 + \sum_{k=1}^{K} y_{ki}^2 \right] \right.$$
$$- \gamma(x,y) - \sum_{r=1}^{R} \sum_{l=1}^{2} \left(c_r^{BI} + c_r^{MI} + c_r^{SI}(x_r^l) \right) - \sum_{r=1}^{R} c_r^D$$
$$- \sum_{r=1}^{R} \sum_{i=1}^{I} \sum_{l=1}^{2} c_{ri}^l(x_{ri}^l) - \sum_{k=1}^{K} c^{OD} - \sum_{k=1}^{K} \sum_{i=1}^{I} \sum_{l=1}^{2} c_{ki}^l(y_{ki}^l)$$
$$\left. - \sum_{i=1}^{I} \sum_{l=1}^{2} P_i^l(\rho_i^l) \left[\sum_{r=1}^{R} d_{ri}^l + \sum_{k=1}^{K} d_{ki}^l \right] \right\}$$

Company's behavior

Costs

- Management costs
- Amortized costs (which include insurance, road tax, total service costs (which depend on the use of the vehicles)
- Total costs of the Regular Drivers
- Shipping costs for delivery (fuel/electricity charge)
- Agreement costs for all Occasional Drivers
- Penalties that company has to pay if customers experience late deliveries, regardless of whether the delay is caused by RVs or ODs.

Company's behavior

Constraints

- Maximum capacity of each RV (per vehicle) of the company:

$$\sum_{i=1}^{I} x_{ri}^{l} \leq \overline{C}_{r}^{l} \quad \forall r = 1, \ldots, R, \ \forall l = 1, 2$$

Company's behavior

Constraints

- Maximum capacity of each RV (per vehicle) of the company:

$$\sum_{i=1}^{I} x_{ri}^{l} \leq \overline{C}_{r}^{l} \quad \forall r = 1, \dots, R, \ \forall l = 1, 2$$

- Delay (given by the difference between the sum of the delivery times to the customers preceding i and the time within which to make the delivery to i):

$$d_{ri}^{l} \geq \sum_{j=1}^{I} \delta_{ji}^{rl} t_{rj}^{l}(x_{r}^{l}) - \overline{T}_{i}, \quad \forall r = 1, \dots, R, \ \forall i = 1, \dots, I, \ \forall l = 1, 2$$

$$d_{ri}^{l} \geq 0, \quad \forall r = 1, \dots, R, \ \forall i = 1, \dots, I, \ \forall l = 1, 2$$

Outline

ODs' behavior

ODs' objective

$$\max \left\{ \sum_{i=1}^{I} \sum_{l=1}^{2} c^{l}_{ki}(y^{l}_{ki}) - \sum_{l=1}^{2} \tilde{c}^{Ml}_{k} - \sum_{l=1}^{2} \tilde{c}^{Sl}_{k}(y^{l}_{k}) - \sum_{i=1}^{I} \sum_{l=1}^{2} \tilde{c}^{l}_{ki}(y^{l}_{ki}) - \alpha_k \sum_{i=1}^{I} V_i d_{ki} \right\}$$

Costs:

- amortized costs of maintaining any type of vehicle
- service costs
- actual shipping costs to customers
- negative evaluation received by the OD in case of delay on the delivery to customers and we consider its economic perception

ODs' behavior

Constraints

- Maximum capacity of OD k, at time t (for both types of vehicles):

$$\sum_{i=1}^{I} y_{ki}^{l} \leq \overline{C}_k^{l} \quad \forall l = 1, 2$$

ODs' behavior

Constraints

- Maximum capacity of OD k, at time t (for both types of vehicles):

$$\sum_{i=1}^{I} y_{ki}^{l} \leq \overline{C}_{k}^{l} \quad \forall l = 1, 2$$

- Availability of OD k to visit a customer with a vehicle of type l:

$$y_{ki}^{l} \leq M\beta_{ki}^{l} \quad \forall i = 1, \ldots, I, \ \forall l = 1, 2$$

ODs' behavior

Constraints

- Maximum capacity of OD k, at time t (for both types of vehicles):

$$\sum_{i=1}^{I} y_{ki}^{l} \leq \overline{C}_k^l \quad \forall l = 1, 2$$

- Availability of OD k to visit a customer with a vehicle of type l:

$$y_{ki}^{l} \leq M\beta_{ki}^{l} \quad \forall i = 1, \ldots, I, \ \forall l = 1, 2$$

- Delay (given by the difference between the total delivery times and the time within which delivery to i must be made):

$$d_{ki}^{l} \geq \sum_{j=1}^{I} \delta_{ji}^{kl} t_{kj}^{l}(y_k^l) - \overline{T}_i, \quad \forall i = 1, \ldots, I, \ \forall l = 1, 2.$$

ODs' behavior

Constraints

- Maximum time available for k, with vehicle l:

$$\sum_{i=1}^{I} t^l_{ki}(y^l_k) \le \overline{T}^l_k, \quad \forall l = 1, 2.$$

Outline

Customers' behavior

Customers' equilibrium conditions

$$p_i^l + \hat{c}_{ri}^l(x_{ri}^{l*}) - P_i^l(\rho_i^l) d_{ri}^l \begin{cases} = \rho_i^{l*} & \text{if } x_{ri}^{l*} > 0 \\ \geq \rho_i^{l*} & \text{if } x_{ri}^{l*} = 0 \end{cases} \quad \forall r = 1, \ldots, R, \ \forall l = 1, 2$$

Customers' behavior

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$$p_i^l + \hat{c}_{ki}^l(y_{ki}^{l*}) - P_i^l(\rho_i^l) d_{ki}^l \begin{cases} = \rho_i^{l*} & \text{if } y_{ki}^{l*} > 0 \\ \geq \rho_i^{l*} & \text{if } y_{ki}^{l*} = 0 \end{cases} \quad \forall k = 1, \dots, K, \ \forall l = 1, 2$$

Customers' behavior

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$$p_i^l + \hat{c}_{ri}^l(x_{ri}^{l*}) - P_i^l(\rho_i^l) d_{ri}^l \begin{cases} = \rho_i^{l*} & \text{if } x_{ri}^{l*} > 0 \\ \geq \rho_i^{l*} & \text{if } x_{ri}^{l*} = 0 \end{cases} \quad \forall r = 1, \ldots, R, \ \forall l = 1, 2$$

$$p_i^l + \hat{c}_{ki}^l(y_{ki}^{l*}) - P_i^l(\rho_i^l) d_{ki}^l \begin{cases} = \rho_i^{l*} & \text{if } y_{ki}^{l*} > 0 \\ \geq \rho_i^{l*} & \text{if } y_{ki}^{l*} = 0 \end{cases} \quad \forall k = 1, \ldots, K, \ \forall l = 1, 2$$

$$\phi_i^l = \sum_{r=1}^{R} x_{ri}^{l*} + \sum_{k=1}^{K} y_{ki}^{l*} \quad \forall i = 1, \ldots, I, \ \forall l = 1, 2$$

Outline

Company's VI

Company's VI

Define:

$$
\begin{aligned}
f^1(X^1) = & \sum_{i=1}^{I}\sum_{l=1}^{2} p_i^l \left[\sum_{r=1}^{R} x_{ri}^l + \sum_{k=1}^{K} y_{ki}^l\right] + N\sum_{i=1}^{I}\left[\sum_{r=1}^{R} x_{ri}^2 + \sum_{k=1}^{K} y_{ki}^2\right] \\
& - \gamma(x,y) - \sum_{r=1}^{R}\sum_{l=1}^{2}\left(c_r^{Bl} + c_r^{Ml} + c_r^{Sl}(x_r^l)\right) - \sum_{r=1}^{R} c_r^D \\
& - \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{l=1}^{2} c_{ri}^l(x_{ri}^l) - \sum_{k=1}^{K} c^{OD} \\
& - \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{l=1}^{2} c_{ki}^l(y_{ki}^l) - \sum_{i=1}^{I} P_i^l(\rho_i^l)\left[\sum_{r=1}^{R} d_{ri} + \sum_{k=1}^{K} d_{ki}\right],
\end{aligned}
$$

where $X^1 = (x, d^1) \in \; K^1 \subseteq \mathbb{R}^{IR(L+1)}$

Company's VI

Theorem

A vector $X^{1*} \in K^1$ is an optimal solution to the Delivery Company Optimization Problem if and only if is a solution to the Variational Inequality:
Find $X^{1*} \in K^1$ such that:

$$\langle \nabla f^1(X^{1*}), X^1 - X^{1*} \rangle \geq 0, \quad \forall X^1 \in K^1$$

Moreover, the variational inequality admits at least one solution.

Company's VI

Theorem

Suppose that, for each costumer i, for each regular vehicle r, for each occasional driver k and for each mean of transport l, the cost functions c_r^{Sl}, c_{ri}^l, c_{ki}^l, P_i^l constitute families of strictly monotone functions w.r.t. their own variables. Moreover, suppose that, the depot management cost function γ is additive, that is:

$$\gamma(x, y) = \gamma^1(x) + \gamma^2(y)$$

and that γ is a strictly convex function. Then, the operator $F^1(X^1) = \nabla f^1(X^1)$ is a strictly monotone function and the solution to the variational inequality is unique.

ODs' VI

ODs' VI

Define:

$$\begin{aligned} f_k^2(X_k^2) \quad = \quad & \sum_{i=1}^{I}\sum_{l=1}^{2} c_{ki}^l(y_{ki}^l) - \sum_{l=1}^{2} \tilde{c}_k^{Ml} - \sum_{l=1}^{2} \tilde{c}_k^{Sl}(y_k^l) \\ & - \sum_{i=1}^{I}\sum_{l=1}^{2} \tilde{c}_{ki}^l(y_{ki}^l) - \alpha_k \sum_{i=1}^{I} V_i d_{ki} \end{aligned}$$

where $X_k^2 = (y_k, d_k^2) \in K_k^2 \subseteq \mathbb{R}^{3I}$

ODs' VI

Theorem

A vector $X^{2*} = (X_k^{2*})_{k=1,\dots,K} \in K^2 = \prod_{k=1}^{K} K_k^2 \subseteq \mathbb{R}^{3KI}$ *is an optimal solution to the optimization problems if and only if is a solution to the variational inequality:*

Find $X^{2*} \in K^2$ *such that:*

$$\sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{l=1}^{2}\left[\frac{\partial \tilde{c}_{ki}^{l}(y_{ki}^{l*})}{\partial y_{ki}^{l}} + \frac{\partial \tilde{c}_{k}^{Sl}(y_{k}^{l*})}{\partial y_{ki}^{l}} - \frac{\partial c_{ki}^{l}(y_{ki}^{l*})}{\partial y_{ki}^{l}} - p_i^l - \delta_l N\right]$$

$$\times (y_{ki}^{l} - y_{ki}^{l*}) + \sum_{k=1}^{K}\sum_{i=1}^{I}[\alpha_k V_i] \times (d_{ki} - d_{ki}^{*}) \geq 0, \quad \forall X^2 \in K^2,$$

where $\delta_l = 1$ *if* $l = 2$, $\delta_l = 0$ *otherwise. Moreover, such a variational inequality admits at least one solution.*

Customers' VI

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Customers' VI

Define:

$$X^3 = (x, y, \rho) \in K^3 := \mathbb{R}^{I(RL+KL+1)}$$

Customers' VI

Theorem

A vector $X^{3*} \in K^3$ satisfies the equilibrium conditions if and only it is a solution to the variational inequality:
Find $X^{3*} \in K^3$ such that:

$$\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{l=1}^{2}\left[p_i^l + \hat{c}_{ri}^l(x_{ri}^{l*}) - P_i^l(\rho_i^{l*})d_{ri}^{l*} - \rho_i^{l*}\right] \times (x_{ri}^l - x_{ri}^{l*})$$

$$+\sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{l=1}^{2}\left[p_i^l + \hat{c}_{ki}^l(y_{ki}^{l*}) - P_i^l(\rho_i^{l*})d_{ki}^{l*} - \rho_i^{l*}\right] \times (y_{ki}^l - y_{ki}^{l*})$$

$$+\sum_{i=1}^{I}\left[\sum_{r=1}^{R} x_{ri}^{l*} + \sum_{k=1}^{K} y_{ki}^{l*} - \phi_i^l(\rho_i^{l*})\right] \times (\rho_i^l - \rho_i^{l*}) \geq 0, \quad \forall X^3 \in K^3$$

Moreover, such a variational inequality admits at least one solution.

VI for the entire Network

Definition (Network Equilibrium)

An equilibrium state of the presented network is reached if the flows between the tiers of the network coincide and the product shipments and prices satisfy the sum of the optimality conditions.

VI for the entire Network

Theorem

A vector $X^* = (X^{1*}, X^{2*}, X^{3*}) \in \mathcal{K}$ is an equilibrium state of the network if and only if it is a solution to the VI given by the sum of the previous VIs, where the feasible set is

$$\mathcal{K} := \left\{ X \in \mathbb{R}^{I(RL+R+KL+K+1)} : \ \textit{all the constraints are satisfied} \right\}.$$

VI for the entire Network

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$$\mathcal{K} := \left\{ X \in \mathbb{R}^{I(RL+R+KL+K+1)} : \ \textit{all the constraints are satisfied} \right\}.$$

Theorem

Under the previous assumptions, the solution to the total VI is unique.

Model with Parcel Lockers

Model with Parcel Lockers

Objective:

Lockers should be placed in areas with high foot traffic, such as shopping districts, metro stations, university campuses. Our aim is to minimize the total cost of a parcel delivery company, by establishing whether to open new lockers and to close other existing lockers in a given limited geographic area.

$$\min \sum_{i=1}^{n} \left[F_i x_i + G_i \cdot (x_i + I_i - y_i) + D_i y_i + Q_i C_i (1 - \rho_i) - R_i Q_i \rho_i\right]$$

Costs:

installation cost of new lockers, management cost of all installed lockers, both existing and newly opened ones, closure/removal cost of closed lockers, delivery cost for couriers at demand nodes, which depend on the demand at each node and the percentage of customers who do not use the lockers, and the revenue.

Model with Parcel Lockers

Constraints:

$$x_i, y_i, z_{ik} \in \{0,1\}, \quad \rho_i \in [0,1] \quad \forall i,k = 1,\ldots,n.$$

$$x_i \leq (1 - l_i), \quad \forall i = 1,\ldots,n;$$

$$y_i \leq l_i, \quad \forall i = 1,\ldots,n;$$

$$\rho_i \geq p_{ik} \cdot (l_k + x_k - y_k), \quad \forall i,k = 1,\ldots,n;$$

$$\rho_i \leq (1 - z_{ik}) + [p_{ik} \cdot (l_k + x_k - y_k)], \quad \forall i,k = 1,\ldots,n;$$

$$\sum_{k=1}^{n} z_{ik} \geq 1, \quad \forall i = 1,\ldots,n$$

Model with Parcel Lockers

Constraints:

- If there is already an open locker at a given node, opening another one is not allowed.
- A locker at a given node can only be closed if it was previously open
- There is a lower and an upper bound for the value of the percentage of customers who go to the nearest open locker

Model with Truck-drone systems

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Objectives:

- Determine which nodes/customers are visited by each drone (and in which launch) and which are visited by the truck;

Model with Truck-drone systems

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- Determine which nodes/customers are visited by each drone (and in which launch) and which are visited by the truck;
- Identify the specific kilometer at which the drone is launched and retrieved;
- Establish the exact route of the truck;

Model with Truck-drone systems

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- Determine which nodes/customers are visited by each drone (and in which launch) and which are visited by the truck;
- Identify the specific kilometer at which the drone is launched and retrieved;
- Establish the exact route of the truck;
- Specify the kilometer at which the drone's battery replacement occurs;

Model with Truck-drone systems

Objectives:

- Determine which nodes/customers are visited by each drone (and in which launch) and which are visited by the truck;
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while

- Minimizing costs and emissions;

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- Minimizing costs and emissions;
- Minimizing the penalty associated with delays;

Model with Truck-drone systems

Objectives:

- Determine which nodes/customers are visited by each drone (and in which launch) and which are visited by the truck;
- Identify the specific kilometer at which the drone is launched and retrieved;
- Establish the exact route of the truck;
- Specify the kilometer at which the drone's battery replacement occurs;

while

- Minimizing costs and emissions;
- Minimizing the penalty associated with delays;
- Minimizing the waiting times (which incur costs) for the truck and drones during recovery.

Model with Truck-drone systems

$$
\begin{aligned}
\min \Bigg\{ & \sum_{i,j} \left[t\left(p_{ij}^{T}\right) + \sum_{n,d} t\left(p_{ij}^{nd,(D)}\right) + \sum_{n,d,k} \left[t\left(d_{ijk}^{(L)}(x_{ijk}^{nd})\right) + t\left(d_{ijk}^{(R)}(y_{ijk}^{nd})\right) \right] \right] + \sum_{n,d} \left[\gamma^{(T)} a_{nd}^{(T)} + \gamma^{(D)} a_{nd}^{(D)} \right] \\
& + \sum_{i,j} \left[\alpha^{(T)} \left(p_{ij}^{(T)}\right) + \sum_{n,d} \alpha^{(D)} \left(p_{ij}^{nd,(D)}\right) + \sum_{n,d,k} \left[\alpha^{(D)} \left(d_{ijk}^{(L)}(x_{ijk}^{nd})\right) + \alpha^{(D)} \left(d_{ijk}^{(R)}(y_{ik}^{nd})\right) \right] \right] + \sum_{i} \beta_i r_i \\
& + M \Bigg[\sum_{k} \sqrt{ \left(\sum_{i,j,n,d} (x_{ijk}^{nd})^2 \right) \left(\sum_{i,j} z_{ij}^2 \right) + \epsilon } + \sqrt{ \sum_{i,j,k,n,d} \left[(x_{ikj}^{nd})^2 (1 - \tilde{x}_{ijk}^{nd})^2 \right] + \epsilon } \\
& + \sqrt{ \sum_{i,j,k,n,d} \left[(y_{ikj}^{nd})^2 (1 - \tilde{y}_{ijk}^{nd})^2 \right] + \epsilon } + \sum_{k} \sqrt{ \left(\sum_{i,j,n,d} (y_{ijk}^{nd})^2 \right) \left(\sum_{i} z_{ik}^2 \right) + \epsilon } \\
& + \sum_{k} \sqrt{ \left(\sum_{i,n,d} (w_{ik}^{nd})^2 \right) \left(\sum_{i} z_{ik}^2 \right) + \epsilon } + \sqrt{ \sum_{i,j} z_{ij}^2 \cdot \tilde{z}_{ij}^2 + \epsilon } + \sqrt{ \sum_{i,j,n,d} (w_{ij}^{nd})^2 (\tilde{w}_{ij}^{nd})^2 + \epsilon } \Bigg] \Bigg\}
\end{aligned}
$$

Costs:

transportation costs, which result from the sum of the costs associated with both trucks and drones, environmental impact, delivery delay penalties, waiting times, which are expressed in cost terms through appropriate weighting coefficients.

Model with Truck-drone systems

$$\sum_{ijk}(x_{ijk}^{nd} + y_{ijk}^{nd}) + \sum_{i}\left(\sum_{n,d} w_{ik}^{nd} + z_{ik}\right) \geq 0, \quad \forall i,j$$

$$(1-\tilde{z}_{ij})d_{ij}^{(T)} = p_{ij}^{(T)}, \quad \forall i,j$$

$$z_{ij}d_{ij}^{(T)} = p_{ij}^{(T)}, \quad \forall i,j$$

$$w_{ij}^{nd} \cdot d_{ij}^{(D)} = p_{ij}^{nd,(D)}, \quad \forall i,j,n,d$$

$$(1-\tilde{w}_{ij}^{nd}) \cdot d_{ij}^{(D)} = p_{ij}^{nd,(D)}, \quad \forall i,j,n,d$$

$$\sum_{i} z_{ij} = \sum_{k} z_{jk}, \quad \forall j$$

$$\sum_{i,k} \tilde{x}_{ikj}^{nd} + \sum_{i} w_{ij}^{nd} = \sum_{k} w_{jk}^{nd} + \sum_{i,k} \tilde{y}_{ikj}^{nd}, \quad \forall j,n,d$$

$$\tilde{x}_{ikj}^{nd} \in [0,1], \quad \forall i,k,j$$

Model with Truck-drone systems

$$\tilde{x}_{ikj}^{nd} \leq x_{ikj}^{nd} \cdot G, \quad \forall i, k, j, n, d$$

$$\tilde{y}_{ikj}^{nd} \in [0, 1], \quad \forall i, k, j, n, d$$

$$\tilde{y}_{ikj}^{nd} \leq y_{ikj}^{nd} \cdot G, \quad \forall i, k, j, n, d$$

$$\sum_{i,j,k} x_{ijk}^{nd} D_k + \sum_{i,j} w_{ij}^{nd} D_j \leq C^d, \quad \forall n, d$$

$$\begin{aligned}
a_{nd}^{(T)} \geq & \left[\sum_{ijk} t \left(d_{ijk}^{(L)} (x_{ijk}^{nd}) \right) + \sum_{i,j} w_{ij}^{nd} t \left(p_{ij}^{nd,(D)} \right) + \sum_{i,j,k} t \left(d_{ijk}^{(R)} (y_{ijk}^{nd}) \right) \right] \\
& - \Bigg[\sum_{i,j,k} \Bigg[\tilde{x}_{ijk}^{nd} t \left(p_{ij}^{(T)} - x_{ij}^{nd} \right) + \sum_{\hat{i},\hat{j},\hat{k}} \Bigg[\tilde{y}_{\hat{i}\hat{j}\hat{k}} t \left(y_{\hat{i}\hat{j}\hat{k}} - p_{\hat{i}\hat{j}}^{(T)} \right) + \sum_{j \leq \tilde{i}, \tilde{j} \leq \hat{i}} t \left(p_{\tilde{i}\tilde{j}}^{(T)} \right) \\
& + \sum_{\bar{d} \neq d} \sum_{\bar{n}} \sum_{j \leq \bar{i}, \bar{j}, \bar{k} \leq \hat{i}} \left[t_{\bar{n}\bar{d}}^{(L)} \tilde{x}_{\bar{i}\bar{j}\bar{k}}^{\bar{n}\bar{d}} + \left[t_{\bar{n}\bar{d}}^{(R)} + a_{\bar{n}\bar{d}}^{(R)} \right] \tilde{y}_{\bar{i}\bar{j}}^{\bar{n}\bar{d}} \right] \Bigg] \Bigg] \Bigg], \quad \forall n, d
\end{aligned}$$

Model with Truck-drone systems

$$
\begin{aligned}
&\sum_{k} z_{ki} \Bigg[\sum_{j \le i-1, l \le i} \Bigg[t\left(p_{jl}^{(T)}\right) + l_{\tilde{j}\tilde{l}}^{(T)} + \sum_{n,d,m} \Big[t_{nd}^{(L)} \tilde{x}_{jlm}^{nd} + \left(t_{nd}^{(R)} + a_{nd}^{(T)} \tilde{y}_{jln}^{nd} \right) \Big] \Bigg] \Bigg] \\
&+ \sum_{n,d,j,l} \tilde{x}_{jli}^{nd} \Bigg[\sum_{\bar{j} \le j-1, \bar{l} \le j} \Bigg[t\left(p_{\bar{j}\bar{l}}^{(T)}\right) + l_{\bar{j}\bar{l}}^{(T)} + \sum_{\bar{n},\bar{d},n} \left(t_{\bar{n}\bar{l}}^{(L)} \tilde{x}_{\bar{j}\bar{l}n} + \left(t_{\bar{n}\bar{d}}^{(R)} + a_{\bar{n}\bar{d}}^{(T)} \right) \tilde{y}_{\bar{j}\bar{l}m}^{\bar{n}\bar{d}} + l_{\bar{n}\bar{d}} \right) \Bigg] \\
&+ t\left(x_{jli}^{nd}\right) + t_{nd}^{(L)} + t\left(d_{jli}^{(L)} (x_{jli}^{nd}) \right) \Bigg] \\
&+ \sum_{n,d,j} w_{ji}^{nd} \Bigg[\sum_{\bar{j} \le i-1, l \le i} \Bigg[t\left(p_{\bar{j}\bar{l}}^{(T)}\right) + l_{\bar{j}\bar{l}}^{(T)} + \sum_{\bar{n},\bar{d},n} \left(t_{\bar{n}\bar{l}}^{(L)} \tilde{x}_{\bar{j}\bar{l}n} + \left(t_{\bar{n}\bar{d}}^{(R)} + a_{\bar{n}\bar{d}}^{(T)} \right) \tilde{y}_{\bar{j}\bar{l}m}^{\bar{n}\bar{d}} + l_{\bar{n}\bar{d}} \right) \\
&+ \tilde{x}_{\bar{j}\bar{l}i}^{nd} \left[t(x_{\bar{j}\bar{l}i}^{nd}) + t_{nd}^{(L)} + t\left(d_{\bar{j}\bar{l}i}^{(L)} \left(x_{\bar{j}\bar{l}i}^{nd} \right) \right) \right] + t\left(p_{\bar{j}\bar{l}}^{nd,(D)} + l_{\bar{j}\bar{l}}^{nd} \right) \Bigg] \Bigg] - r_i \le \bar{T}_i, \quad i
\end{aligned}
$$

$$a_{nd}^{(D)} \ge -a_{nd}^{(T)}, \quad \forall n, d$$

$$\sum_{i,j,k} \tilde{x}_{ijk}^{nd} \le 1, \quad \forall n, d$$

$$\sum_{i,j,k} \tilde{x}_{ijk}^{nd} = \sum_{\bar{i}\bar{j}\bar{k}} \tilde{y}_{\bar{i}\bar{j}\bar{k}}^{nd}, \quad \forall n, d$$

Model with Truck-drone systems

Constraints:

- Every customer node must be visited exactly once.
- If the truck arrives at a node, it must also depart from that same node.
- For each drone launch, the droneâs carried load must not exceed its maximum capacity.
- Every launched drone must be retrieved.
- A drone can be launched on an arc only if the truck actually travels along that arc.
- A drone can be recovered along an arc only if the truck travels along that arc.
- Each drone can perform multiple deliveries with the same battery until its energy is depleted.
- ...

A Numerical Simulation with Crowdsoursing

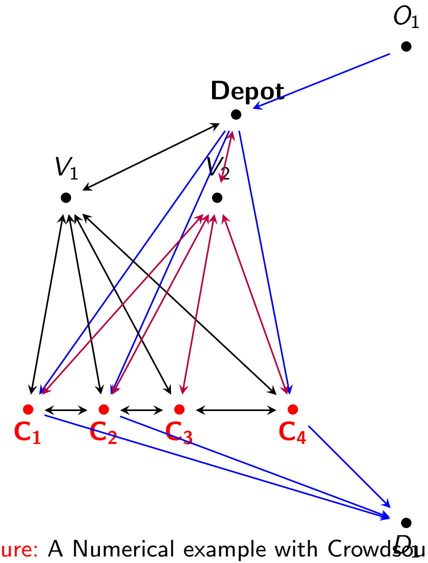

Figure: A Numerical example with Crowdsoursing

A Numerical Simulation with Crowdsoursing

Data

- 2 RDs with a petrol/diesel vehicle and an electric vehicle
- $\overline{C}_1^1 = 100, \ \overline{C}_1^2 = 70, \ \overline{C}_2^1 = 150, \ \overline{C}_2^2 = 90$
- 1 occasional driver with an electric vehicle
- $\overline{C}_k^2 = 60$
- 4 customers
- $\beta_{13}^1 = \beta_{13}^2 = 0, \ \beta_{11}^l = \beta_{12}^l = \beta_{14}^l = 1$

A Numerical Simulation with Crowdsoursing

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Two Simulations

S1: without occasional drivers;

S2: with occasional driver.

A Numerical Simulation with Crowdsourcing

S1	$i=1$	$i=2$	$i=3$	$i=4$	**Objective Function**
x_{1i}^{1*}	0	0	0	0	
x_{1i}^{2*}	18.84	8.69	24.52	17.95	
x_{2i}^{1*}	0	0	0	0	
x_{2i}^{2*}	21.16	11.31	15.48	12.05	
y_{1i}^{1*}	-	-	-	-	
y_{1i}^{2*}	-	-	-	-	11,728

Table: Optimal solutions in S1

A Numerical Simulation with Crowdsoursing

S1	$i=1$	$i=2$	$i=3$	$i=4$	Objective Function
x_{1i}^{1*} x_{1i}^{2*}	0 18.84	0 8.69	0 24.52	0 17.95	
x_{2i}^{1*} x_{2i}^{2*}	0 21.16	0 11.31	0 15.48	0 12.05	
y_{1i}^{1*} y_{1i}^{2*}	- -	- -	- -	- -	11,728

Table: Optimal solutions in S1

S2	$i=1$	$i=2$	$i=3$	$i=4$	Objective Function
x_{1i}^{1*} x_{1i}^{2*}	0 5.53	0 2.66	0 26.44	0 11.70	
x_{2i}^{1*} x_{2i}^{2*}	0 5.33	0 2.55	0 13.56	0 5.87	
y_{1i}^{1*} y_{1i}^{2*}	- 29.14	- 14.79	- 0	- 12.43	12,150

Table: Optimal solutions in S2

A Numerical Simulation with Crowdsourcing

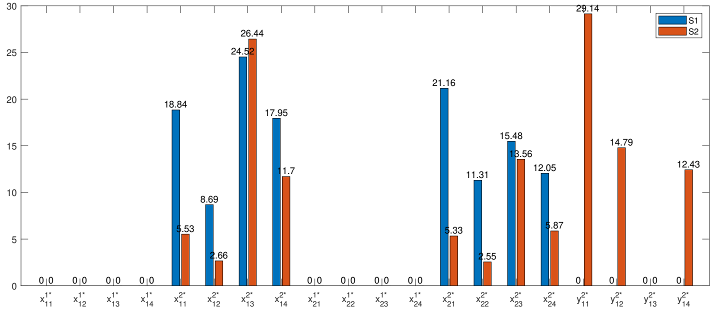

Figure: Comparison of optimal solutions in S1 and S2


THANK YOU
FOR YOUR
ATTENTION