Optimization of green vehicles and crowdsorcing in the last mile deliveries

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Joint paper with G. Colajanni - D. Sciacca

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Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

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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

1. Introduction

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2. Literature overview

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   - Company's behavior
   - ODs' behavior
   - Customers' behavior

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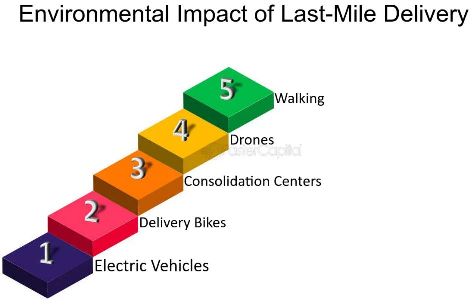
E-commerce

- 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

Crowdsoursing

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- 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

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

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3. 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

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2. C. Archetti, F. Guerriero, G. Macrina, *The online vehicle routing problem with occasional drivers*, Computers and Operations Research, 127, 2021
3. 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
4. D. Yang, M.F. Hyland, R. Jayakrishnan, *Delivery Problem at Scale through a Set-Partitioning Formulation and Novel Decomposition Heuristic*, Transportation Research Part E: Logistics and Transportation Review, 188, August 2024, 103633

Literature Overview

1. G. Colajanni, P. Daniele, A. Nagurney, *Centralized Supply Chain Network Optimization with UAV-based last mile deliveries*, Tranportation Research Part C, 155, 2023, 104316

The Mathematical Model

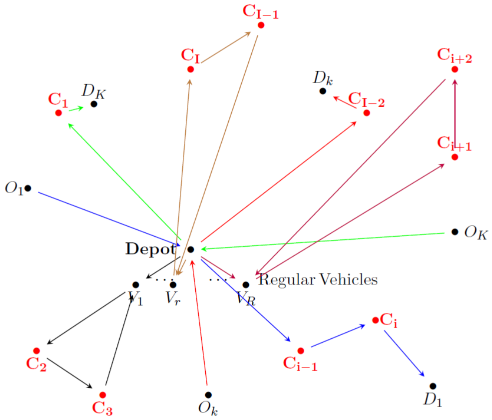

Figure: Network topology

The Mathematical Model

Assumptions:

1. All customers' requests have to be satisfied

The Mathematical Model

Assumptions:

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

The Mathematical Model

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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

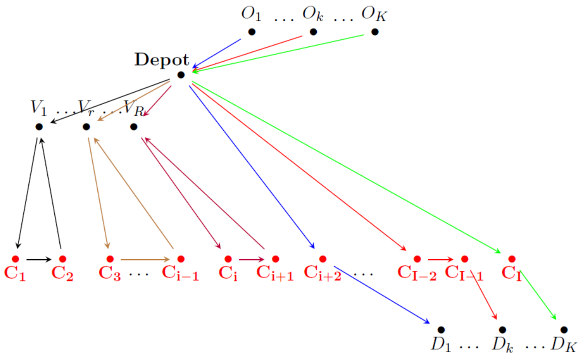

Figure: Supply chain representation

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Company's behavior

Company's objective

$$\max \left\{ \sum_{i=1}^{I} \sum_{l=1}^{2} p_i^l \left[\sum_{r=1}^{R} x_{ri}^l + \sum_{k=1}^{K} y_{ki}^l \right] + N \sum_{i=1}^{I} \left[\sum_{r=1}^{R} x_{ri}^2 + \sum_{k=1}^{K} y_{ki}^2 \right] \right.$$

Company's behavior

Company's objective

$$\max \Bigg\{ \sum_{i=1}^{I} \sum_{l=1}^{2} p_i^l \left[\sum_{r=1}^{R} x_{ri}^l + \sum_{k=1}^{K} y_{ki}^l \right] + N \sum_{i=1}^{I} \left[\sum_{r=1}^{R} x_{ri}^2 + \sum_{k=1}^{K} y_{ki}^2 \right]$$

$$-\gamma(x,y) - \sum_{r=1}^{R} \sum_{l=1}^{2} \left(c_r^{BI} + c_r^{MI} + c_r^{SI}(x_r^l) \right) - \sum_{r=1}^{R} c_r^D$$

$$- \sum_{r=1}^{R} \sum_{i=1}^{I} \sum_{l=1}^{2} c_{ri}^l(x_{ri}^l) - \sum_{k=1}^{K} c^{OD} - \sum_{k=1}^{K} \sum_{i=1}^{I} \sum_{l=1}^{2} c_{ki}^l(y_{ki}^l)$$

Company's behavior

Company's objective

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

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:

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

- 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):

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

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

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ODs' behavior

ODs' objective

$$\max\left\{\sum_{i=1}^{I}\sum_{l=1}^{2} c_{ki}^{l}(y_{ki}^{l}) - \sum_{l=1}^{2}\tilde{c}_{k}^{Ml} - \sum_{l=1}^{2}\tilde{c}_{k}^{Sl}(y_{k}^{l}) - \sum_{i=1}^{I}\sum_{l=1}^{2}\tilde{c}_{ki}^{l}(y_{ki}^{l})\right.$$

ODs' behavior

ODs' objective

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

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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:

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

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Customers' behavior

Customers' equilibrium conditions

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

Customers' behavior

Customers' equilibrium conditions

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

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

Customers' behavior

Customers' equilibrium conditions

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

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

$$\phi_i^l(\rho_i^{l*}) \begin{cases} =\sum_{r=1}^{R} x_{ri}^{l*}+\sum_{k=1}^{K} y_{ki}^{l*} & \text{if } \rho_i^{l*}>0 \\ \leq \sum_{r=1}^{R} x_{ri}^{l*}+\sum_{k=1}^{K} y_{ki}^{l*} & \text{if } \rho_i^{l*}=0 \end{cases} \quad \forall l=1,2$$

VI formulations

Definition (Variational Inequality Formulation)

Given a continuous function $F : K \to \mathbb{R}^N$, where $K \subset \mathbb{R}^N$ is a given (non empty) convex set, the finite-dimentional variational inequality problem consists in determining a vector $X^* \in K$ such that

$$\langle F(X^*), X - X^* \rangle = \sum_{i=1}^{N} F_i(X)(X_i - X_i^*) \geq 0, \quad \forall X \in K.$$

VI formulations

Theorem

Let X^* be a solution to the optimization problem:

$$\min_K f(X)$$

where f is a continuously differentiable function and K is a closed convex set. Then, X^* is a solution to the variational inequality problem $VI(F, X)$:

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

where $F(X) \equiv \nabla f(X)$. Moreover, if $f(x)$ is a convex function and X^* is a solution to $VI(F, K)$, then X^* is a solution to the optimization problem.

VI formulations

Theorem

If K is a compact convex set, then $VI(F,K)$ admits at least one solution X^*. Moreover, if $F(X)$ is strictly monotone on K, that is

$$\langle F(X^1) - F(X^2), X^1 - X^2 \rangle > 0, \quad \forall X^1,\ X^2 \in K,\ X^1 \neq X^2,$$

the solution is unique.

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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 $F^1(X^1)$ is a strictly monotone function and the solution to the variational inequality is unique.

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ODs' VI

OD's VI

Define:

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

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

ODs' VI

Theorem

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

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

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

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

Customers' VI

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.

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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

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

VI for the entire Network

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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

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

Theorem

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

A Numerical Simulation

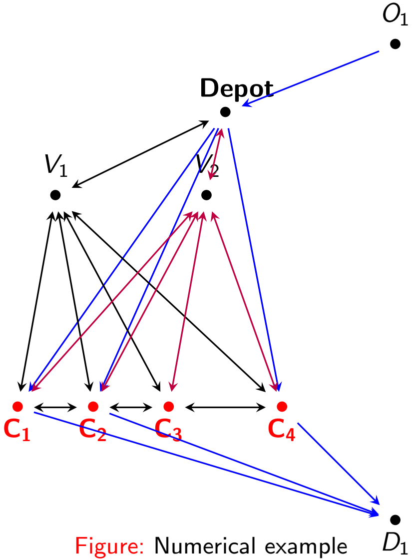

Figure: Numerical example

Numerical Simulation

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
- $\beta_{13}^1 = \beta_{13}^2 = 0, \ \beta_{11}^l = \beta_{12}^l = \beta_{14}^l = 1$

Numerical Simulation

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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
- $\beta_{13}^1 = \beta_{13}^2 = 0, \ \beta_{11}^l = \beta_{12}^l = \beta_{14}^l = 1$

Two Simulations

S1: without occasional drivers;

S2: with occasional drivers.

A Numerical Simulation

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

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

S2	$i=1$	$i=2$	$i=3$	$i=4$	**Objective Function**
x_{1i}^{1*}	0	0	0	0	
x_{1i}^{2*}	5.53	2.66	26.44	11.70	
x_{2i}^{1*}	0	0	0	0	
x_{2i}^{2*}	5.33	2.55	13.56	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

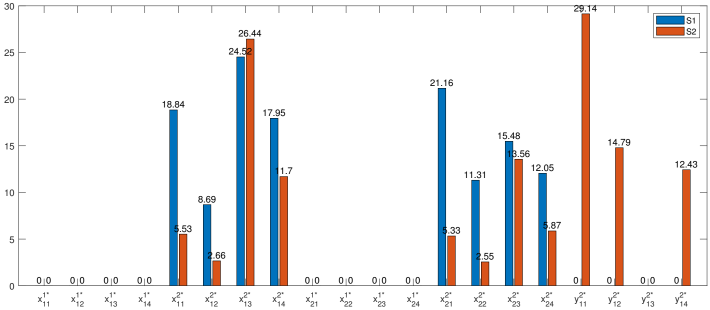

Figure: Comparison of optimal solutions in S1 and S2


THANK YOU
FOR YOUR
ATTENTION