How Parcel Lockers and Crowd-Sourcing Shape Urban Delivery Systems

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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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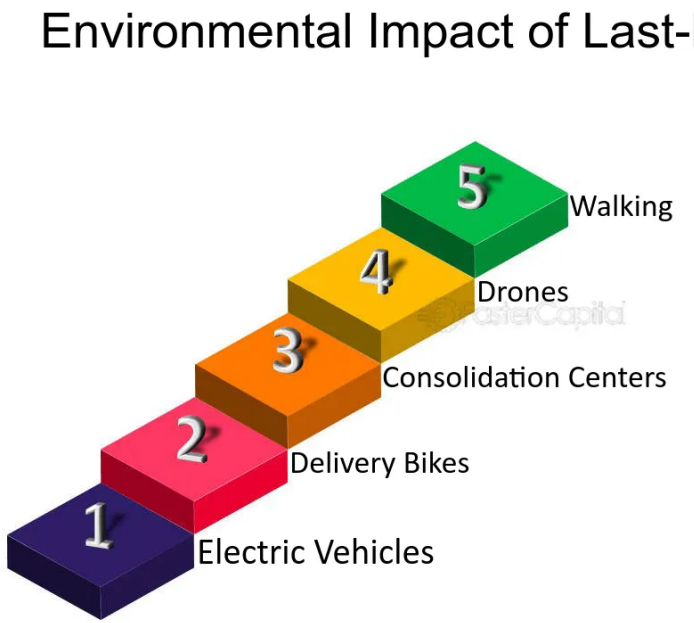
E-commerce

- 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

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).

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 consumers:

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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

Remarks:

- The effectiveness of parcel lockers depends on their strategic placement.
- Many factors must be considered to optimize their deployment: analyzing consumer behavior and demographics helps determine the most efficient locations, ensuring that lockers are positioned where demand is highest.
- Traffic flow and accessibility play a crucial role, as lockers should be placed in areas with high foot traffic, such as shopping districts, metro stations, and university campuses.

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The Mathematical Model

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Objective:

The optimization model aims to minimize the total operational cost (including installation, management, and removal costs, as well as delivery costs and revenue flows) incurred by a parcel delivery company through strategic decisions on the installation of new parcel lockers and the decommissioning of existing ones within a defined urban area.

The Mathematical Model

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The optimization model aims to minimize the total operational cost (including installation, management, and removal costs, as well as delivery costs and revenue flows) incurred by a parcel delivery company through strategic decisions on the installation of new parcel lockers and the decommissioning of existing ones within a defined urban area.

Assume we have n nodes, which may correspond either to a location where a parcel locker already exists or to a potential site where a locker could be installed.

The Mathematical Model

Decision Variables:

$$x_i = \begin{cases} 1 & \text{if a locker needs to be opened/installed at node } i \\ 0 & \text{otherwise} \end{cases}$$

$$y_i = \begin{cases} 1 & \text{if a locker at node } i \text{ needs to be closed/removed} \\ 0 & \text{otherwise} \end{cases}$$

Parameters:

- $\rho_i \in [0, 1]$: percentage of customers at node i who go to the nearest locker (this variable depends on the distance to the nearest open locker)

The Optimization Problem

$$\min \sum_{i=1}^{n} [F_i x_i$$

installation costs of new lockers

The Optimization Problem

$$\min \sum_{i=1}^{n} [F_i x_i + G_i \cdot (x_i + l_i - y_i)$$

management cost of all installed lockers, both existing and new ones

The Optimization Problem

$$\min \sum_{i=1}^{n} [F_i x_i + G_i \cdot (x_i + l_i - y_i) + D_i y_i$$

closure/removal cost of closed lockers

The Optimization Problem

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

delivery cost for couriers at demand nodes

The Optimization Problem

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

revenue (to be maximized) from orders picked up by customers at the lockers

The Optimization Problem

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

Constraints:

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

If there is already an open locker at a given node, opening another one is not allowed

The Optimization Problem

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

Constraints:

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

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

A locker at a given node can only be closed if it was previously open (i.e., a locker already existed at that node)

The Optimization Problem

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

Constraints:

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

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

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

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

lower and upper bounds for the value of the maximum percentage of customers who go to the nearest open locker

The Optimization Problem

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

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

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

Domain of the variables

Numerical Simulations

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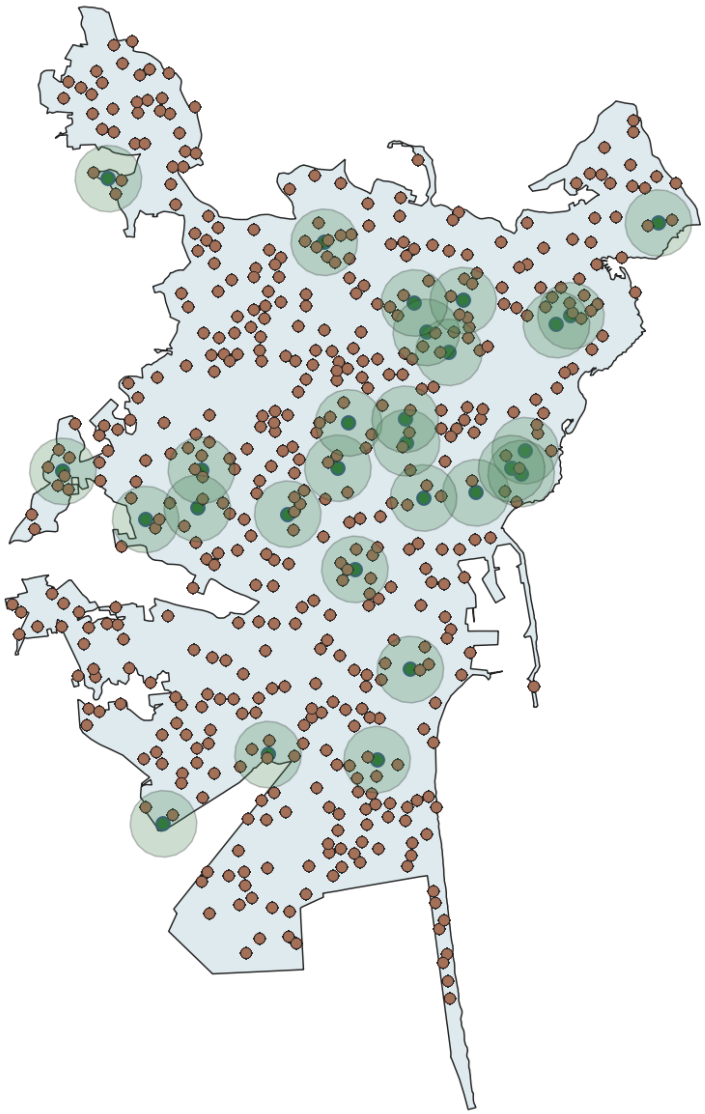

Numerical Simulations

Costs:

- fixed installation cost for opening a new locker was set to 1,500 € per site ($F_i = 1500$)
- cost of decommissioning an existing locker was assumed to be 1,000 € ($D_i = 1000$)
- unit delivery cost per order was set at 2.50 € ($C_i = 2.5$)
- revenue generated per successful delivery was set at 7.00 € ($R_i = 7$)

Numerical Simulations

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Optimal Solution

- computational time: 23.43 seconds
- optimized total cost: 199,243.95 €
- 92 new lockers at selected demand nodes
- 6 existing lockers decommissioned
- final network configuration: 111 active lockers

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Comparison

the existing locker configuration provided service to only 110 out of 500 demand nodes, representing 22% coverage within a 400-meter service radius.
After optimization, the locker network achieved full coverage, effectively serving all 500 demand nodes and thereby attaining a 100% coverage rate.

Optimal Spatial Distribution

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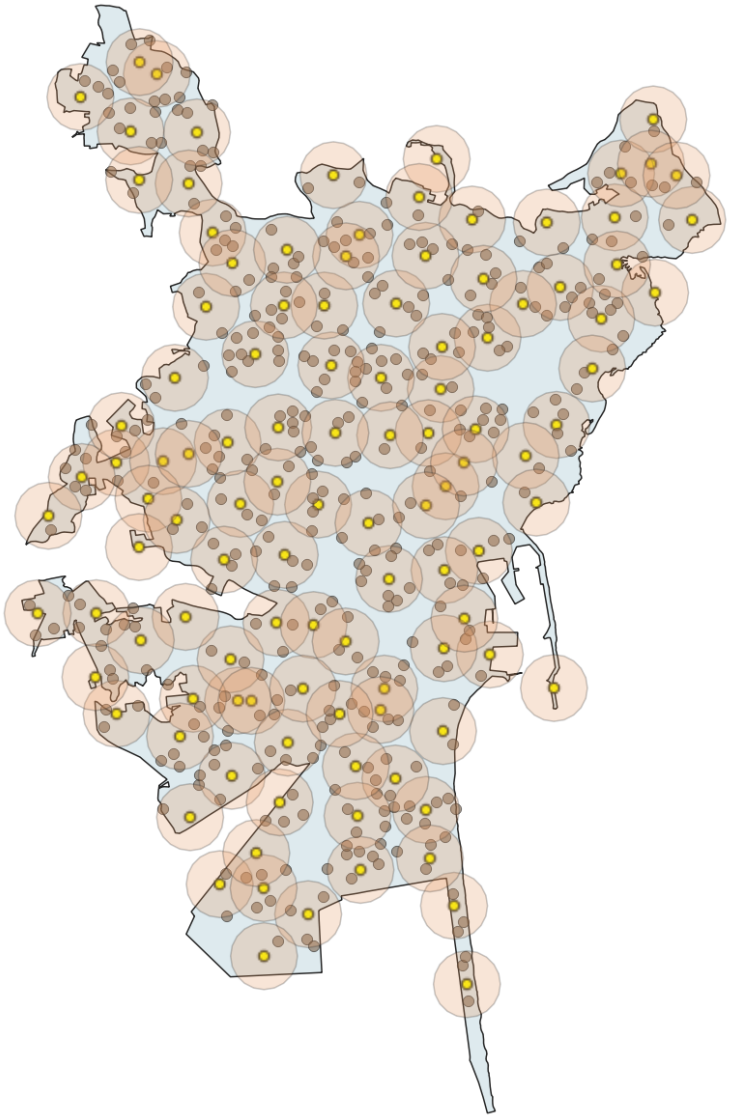

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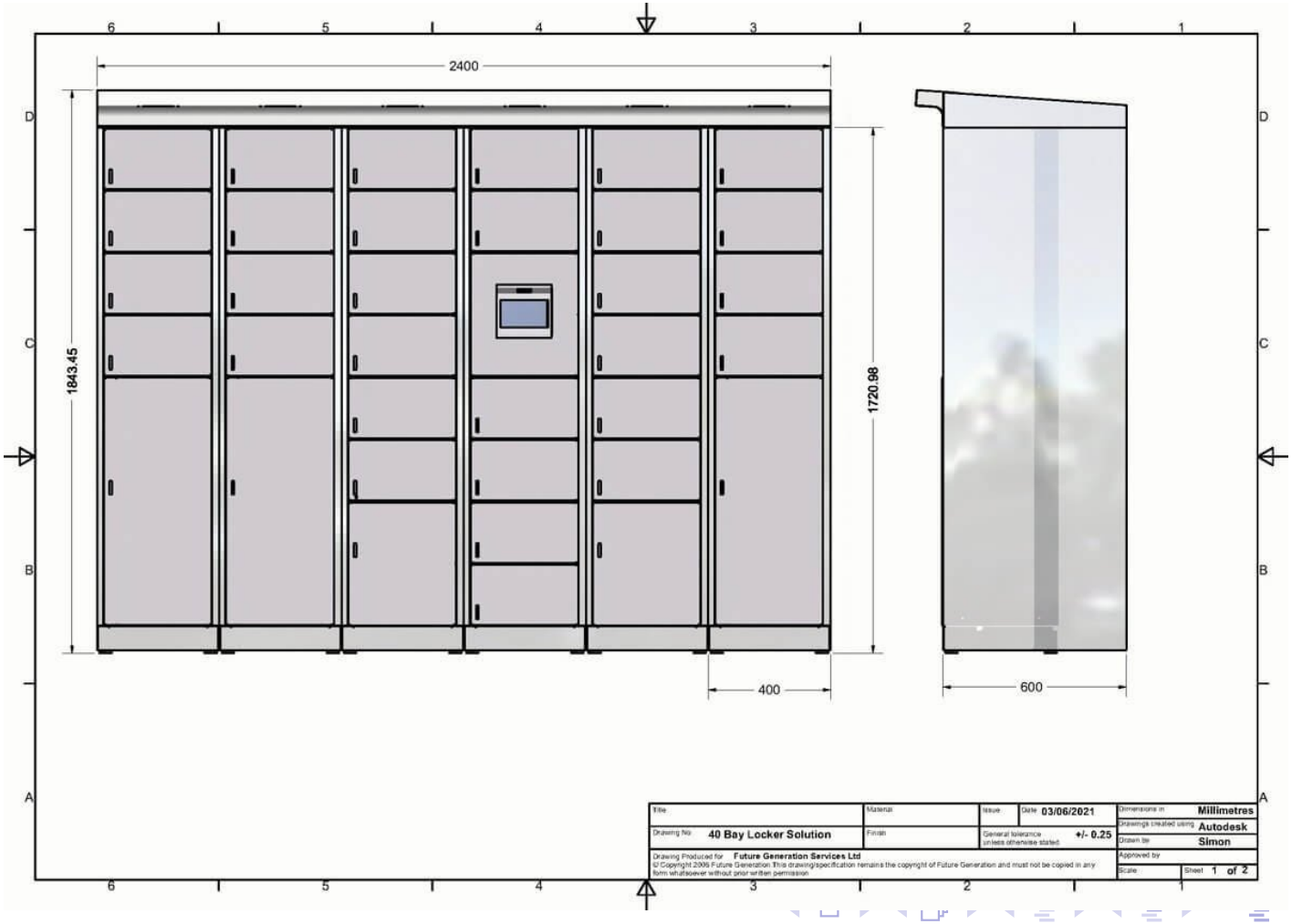
Model with different sizes

- Using parcel lockers of different sizes is more convenient because it avoids wasting space and makes it easier to handle both small and large packages efficiently.



The Mathematical Model

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Decision Variables:

- $x_{ij} \in \mathbb{R}_+$: fraction of a Standard Module of type j installed at node i;
- $y_{ij} \in [0, 1]$: fraction of the existing locker of type j at node i to be decommissioned;

Parameters:

- K_j : maximum delivery capacity of a locker of type j;
- N_j : total number of slots contained in one full standard unit (rack) of type j;
- W_i : maximum capacity of all the modules at node i.

The Optimization Model

Objective Function

Minimize the total system costs associated with the parcel locker network: installation costs for new modular units, management expenses, decommissioning costs related to existing locker sites.

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Minimize the total system costs associated with the parcel locker network: installation costs for new modular units, management expenses, decommissioning costs related to existing locker sites.

Constraints

- the total physical dimension of all installed modules at node i does not exceed a predefined and allowed maximum capacity;
- the total volume of parcels assigned to a locker at node i does not exceed its physical storage capacity.
- ...

Outline

Crowd-Sourcing Delivery System

Benefits:

- Reduced operational costs
- Increased delivery flexibility
- Environmental benefits
- Job creation opportunities

Real-World Examples:

- Amazon Flex: \$18–\$25/hour
- Walmart: Fast delivery program
- Food delivery: Deliveroo, JustEat, Glovo

Outline

The Model Framework: Players and Strategies

Tripartite evolutionary game model.

Players

- Logistics Providers (LP)
- Independent Drivers (ID)
- Consumers (C)

Strategies

- LP: Regular crowd-sourcing (RC) vs Occasional (OC)
- ID: Cooperate (CP) vs Not cooperate (NCP)
- C: Express delivery (ED) vs Standard delivery (SD)

Key Features of the Model

- Evolutionary game framework (no full rationality)
- Introduction of a soft reputation mechanism:
  - Bonus for trustworthy drivers
  - Penalty when untrustworthy drivers dominate
- Incentives shared among players:
  - Revenue-sharing
  - Cost-sharing
- Compensation for delays

Goal: study long-run behavioral outcomes

Model Parameter

Parameter	Description	Value
π_L^+	Revenue of L under crowd-sourcing	$\pi_L^+ > 0$
π_L	Revenue of L under occasional crowd-sourcing	$\pi_L > 0$
π_D	Revenue of D under independent delivery	$\pi_D > 0$
R	Crowd-sourcing delivery service revenue	$R > 0$
π_C	Satisfaction benefit of C	$\pi_C > 0$
π_C^+	Additional satisfaction benefit of C under regular crowd-sourcing	$\pi_C^+ > 0$
c_t	Transportation cost for standard home-delivery	$c_t > 0$
c_e	Transportation cost for express home-delivery	$c_e > c_t$
c_p	Cost of L for using crowd-sourcing platform	$c_p > 0$
c^+	Additional cost of C for express delivery	$c^+ > 0$
S	Environmental benefit of C for crowd-sourcing	$S > 0$
d	Late delivery compensation paid by L to C	$d > 0$
T	Proportion of trustworthy drivers registered on the platform	$0 < T < 1$
p	Penalty term for D under $1 - T$ untrustworthy drivers	$p > 0$
B	Bonus for D under T trustworthy drivers	$B > 0$
l_L	Potential loss of L for inefficiency	$l_L > 0$
l_C	Potential loss of C for inefficiency	$l_C > 0$
α	Revenue-sharing parameter	$0 < \alpha < 1$
β	Cost-sharing parameter	$0 < \beta < 1$

Payoff Matrix

		C	
L	**D**	**ED** z	**SD** $1-z$
RC x	**CP** y	$\pi_L^+ + \alpha R - \beta c_e - c_p - d$ $(1-\alpha)R - (1-\beta)c_e + BT - p(1-T)$ $\pi_C + \pi_C^+ + S + d - c^+$	$\pi_L^+ + \alpha R - \beta c_t - c_p$ $(1-\alpha)R - (1-\beta)c_t + BT - p(1-T)$ $\pi_C + \pi_C^+$
	NCP $1-y$	$\pi_L^+ + R - c_e - c_p - d$ π_D $\pi_C + d - c^+$	$\pi_L^+ + R - c_t - c_p$ π_D π_C
OC $1-x$	**CP** y	$\pi_L - l_L - d$ $R - c_e + BT - p(1-T)$ $\pi_C + d - c^+$	$\pi_L - l_L$ $R - c_t + BT - p(1-T)$ π_C
	NCP $1-y$	$\pi_L + R - l_L - c_e - d$ π_D $\pi_C + d - c^+ - l_C$	$\pi_L + R - l_L - c_t$ π_D π_C

Replicator Dynamics

$$\begin{aligned}
\dot{x} &= x(1-x)(U_{RC} - U_{OC}) \\
&= x(1-x)(\pi_L^+ + \alpha R y + I_L - \pi_L - c_p - (1-z)\beta c_t y - \beta c_e y z), \\
\dot{y} &= y(1-y)(U_{CP} - U_{NCP}) \\
&= y(1-y)(\pi_D + (1-\alpha x)R - c_t(1-\beta x)(1-z) - c^e z(1-\beta x) \\
&+ BT - (1-T)p), \\
\dot{z} &= z(1-z)(U_{ED} - U_{SD}) \\
&= z(1-z)(d + Sxy - c^+ + I_C(x + y - xy - 1)).
\end{aligned}$$

- Successful strategies spread
- Poorly performing strategies disappear
- Dynamic path toward stable equilibria

Equilibrium Analysis

- 8 pure-strategy equilibria
- Stability via Jacobian eigenvalues
- Only two asymptotically stable equilibria

Assumptions:

$$R - c_t + BT - p(1-T) > 0,$$
$$\pi_L^+ + \alpha R - \beta c_t - c_p - \pi_L + l_L > 0,$$
$$\pi_L^+ - \pi_L > 0,$$

$$R - c_e + BT - p(1-T) > 0,$$
$$\pi_L^+ + \alpha R - \beta c_e - c_p - \pi_L + l_L > 0,$$
$$d - c^+ < 0.$$

Stable Outcomes

- $(1,1,0)$: RC, CP, SD
- $(1,1,1)$: Full cooperation, express delivery

Outline

Numerical Simulations

Parameters:

π_L^+	π_L	π_D	R	c_t
[2.5; 5]	[2; 5]	[2; 2.5]	[3.5; 4.3]	[1; 1.8]
c_e	c_p	c^+	p	B
[1; 1.8]	[2; 2.5]	[0.1; 2.6]	[1.8; 4.5]	[1; 3]
d	T	l_L	l_C	S
[0.2, 0.7]	[0.1, 0.9]	[0.3; 1]	[0.3; 1]	[0.1; 1]
α	β			
[0; 1]	[0; 1]			

Initial strategies: $x = 0.5$, $y = 0.5$, and $z = 0.5$.

Simulation Results Visualization

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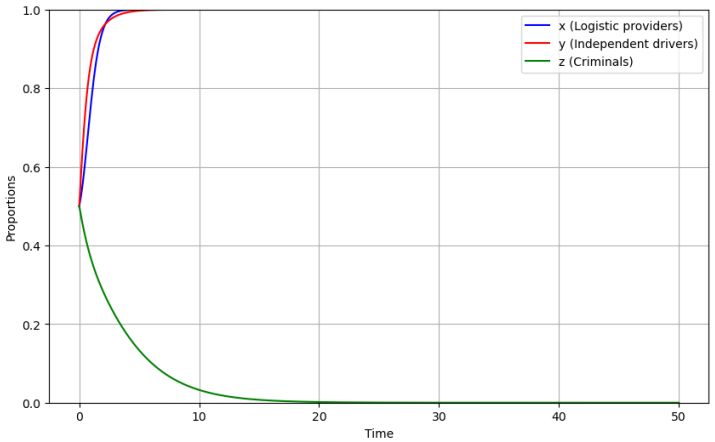
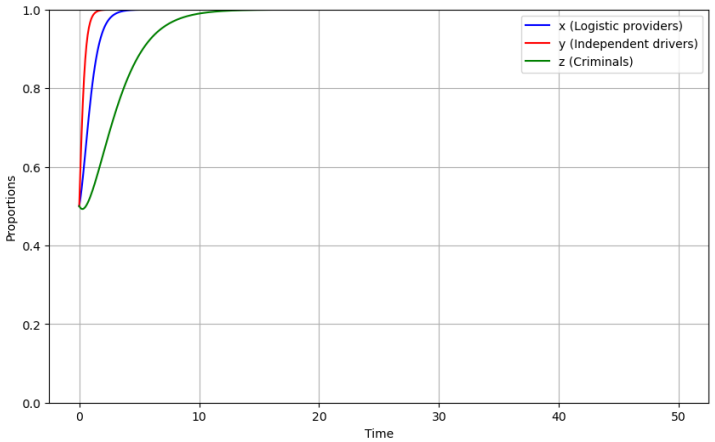


(a) Evolution to $(1, 1, 0)$ (frequence 52.23%)



(b) Evolution to $(1, 1, 1)$ (frequence 46.63%)

Sensitivity Analysis

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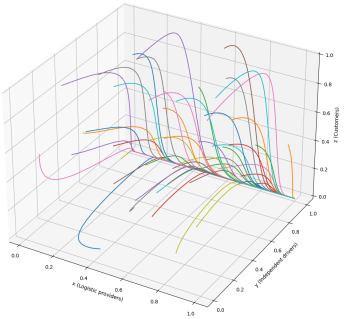
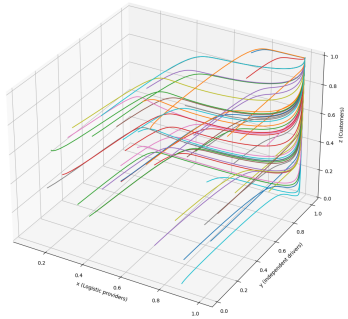
The system is robust to changes in initial probabilities.

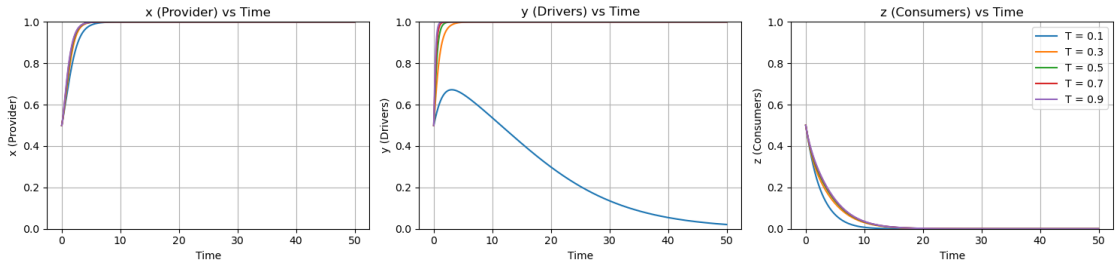


(a) Evolution to $(1, 1, 0)$



(b) Evolution to $(1, 1, 1)$

Changes in trustworthy drivers evolve to the unstable point $(1, 0, 0)$.



Strategic Insights

- Crowd-sourced delivery works only with aligned incentives
- Reputation stabilizes cooperation
- Evolutionary games capture adaptive behavior

Stakeholders:

- Providers: Reputation influences crowdsourcing
- Drivers: Build reputation through cooperation
- Customers: Compensation drives express choice

Policy Levers:

- $\uparrow \alpha$ or $\downarrow \beta$ sustains RC
- Reputation mechanisms enforce cooperation
- Environmental incentives
- Platform governance

Infrastructure + behavior + reputation = sustainable delivery