ROAR-NET Cost Action CA22137
First Training School

Integrating Passenger Transport and Parcel Deliveries: An example of Share-a-Ride problem in Luxembourg

D. H. Stolfi, W. Mtalaa

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

ROAR NET

Funded by the European Union

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

AGENDA

- Research at LIST
- Last Mile Delivery overview
- Combining Passenger and Parcel Transport
- Description of the Problem
- Mathematical Model
- Algorithms Developed
- Numerical Experiments
- Conclusion and Perspectives

THE LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY
A REFERENCE IN RESEARCH AND INNOVATION FOR A DIGITALIZED, RESILIENT & SUSTAINABLE SOCIETY

Created in 2015 | Active in 4 fields

ENVIRONMENT
+
200
employees

INFORMATICS
+
100
employees

MATERIALS
+
200
employees

SPACE
+
20
employees

HUMAN RESOURCES

756 employees

34% women

61 nationalities

114 people recruited

78% researchers or Innovation experts

83 PhD students hosted

2024 figures (on 31 December)

R&D PROJECTS IN PROGRESS IN 2024

148
national competitive projects

78
international competitive projects

7,11%
of income from services

159
collaborative projects & similar

∑ 475
total of RDI projects & contracts

2023 figures

SCIENCE AND TRANSFER IN 2024

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177

scientific articles in 1st quartile journals

9

spin-offs (existing for 3 years or more)

25

filed patents

16

paid licences

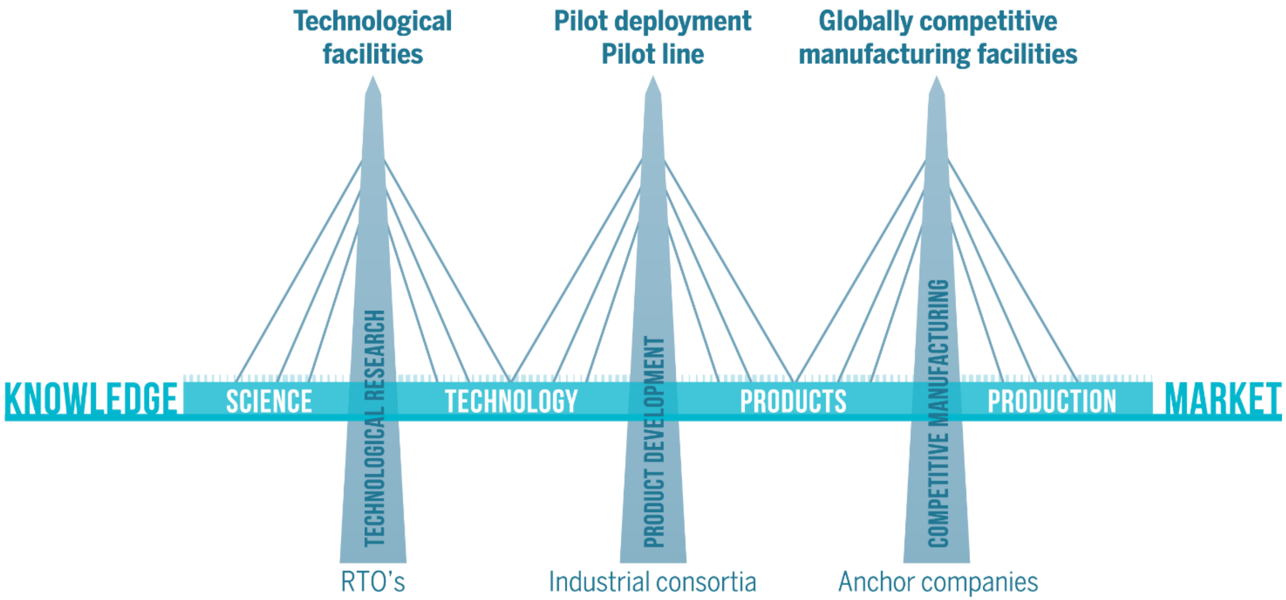
4 AREAS OF RESEARCH EXCELLENCE

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

Working across the entire innovation chain

- Fundamental & applied research
- Incubation & transfer of technologies
- Policy support
- Doctoral & post-doctoral training

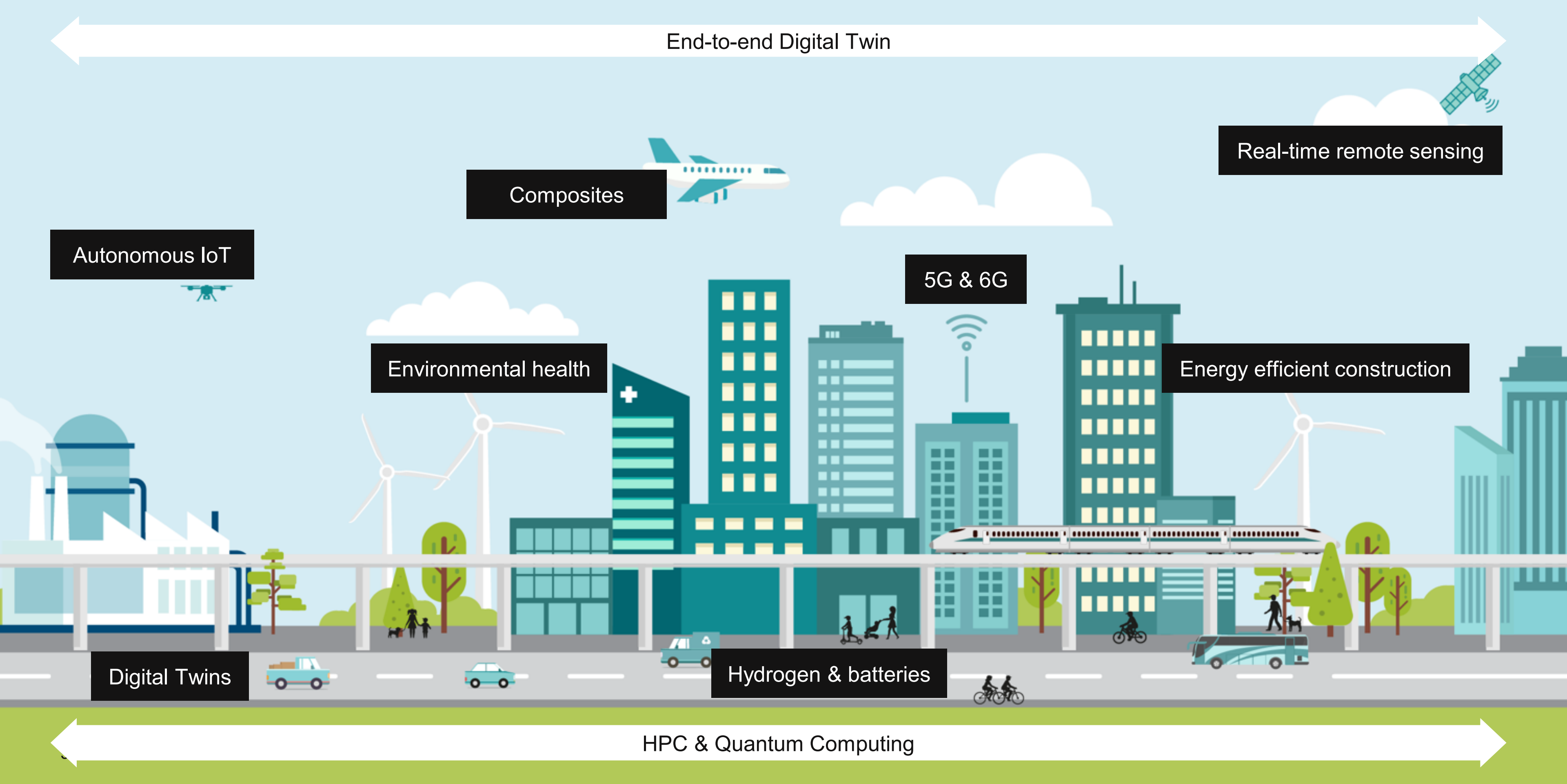
BUILDING A BRIDGE BETWEEN LUXEMBOURG RESEARCH AND BUSINESS



Technology Readiness Level (TRLs)

1. Basic principles observed
2. Technology concept formulated
3. Experimental proof of concept
4. Technology validation in laboratory
5. Technology validation in relevant environment
6. Demonstration in relevant environment
7. Demonstration in operational environment
8. System complete and qualified
9. Successful mission operations
10. Mass Production

DIGITALISATION AND SUSTAINABILITY: 12 LIST CORE TECHNOLOGIES



LIST INFORMATICS

Responsible
Data Science
& Analytics

Reliable
Distributed
Systems

Software
Engineering
RDI

AIDA
Lab

6G
Networks

Explainable
AI

Digital Twin
Technologies

LIST

AI & Data Analytics

- Data science
- AI prototyping
- Software development
- Research data management
- Infrastructure provision

5 PARTNERSHIP MODELS

A solution for every problem

LIST PARTNERSHIP MODELS

- Strategic program
- Strategic partner
- Collaborative project
- Service contract
- IP licensing

LIST VENTURES

LIST's Tech Venture Builder and Start-up / Industry Cooperation

LIST Entrepreneurs

Are you a researcher at LIST planning to set up a company?

LIST Researchers

Are you a researcher at LIST with an interest in entrepreneurship?

Startups & Entrepreneurs

Are you a Startup looking for a tecnological partner?

Entrepreneurial Corporations

Are you a company interested in launching new businesses?

Investors

Are you an investor looking for technological deep moat investments?

THANKS TO

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Our line Ministry

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Administration des ponts et chaussées

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Fonds National de la Recherche Luxembourg

LUXINNOVATION #MakingInnovationHappen

RESEARCH LUXEMBOURG

LUXEMBOURG INSTITUTE OF HEALTH RESEARCH DEDICATED TO LIFE

LISER

uni.lu UNIVERSITÉ DU LUXEMBOURG

LNS LUXEMBOURG

SECURITY MADEIN.LU

ILR INSTITUT LUXEMBOURGEOIS DE RÉGULATION

CNPD COMMISSION NATIONALE POUR LA PROTECTION DES DONNÉES

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

esa

#BelieveInSmall

Forestry and Climate Change Fund

ibpt

IFSB

INCERT Because it's always a matter of security

Institut supérieur de l'économie ISEC LUXEMBOURG

LUXEMBOURG SPACE AGENCY

LCL Luxembourg Centre for Logistics and Supply Chain Management

SEBES

SMA

SmartEnds

UNIVERSITÉ DE LORRAINE

Ville de Differdange

VILLE DE LUXEMBOURG

THANKS TO

LAST MILE DELIVERY OVERVIEW

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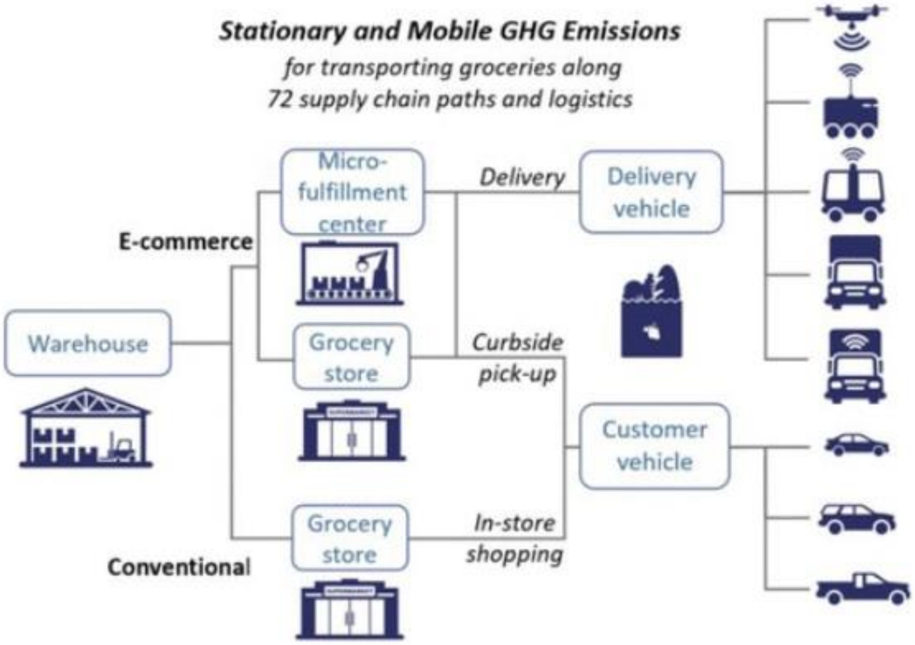
Final leg of the logistics chain, from hub to consumer

- Key issues: High costs, traffic congestion, delivery delays
- Growing demand from e-commerce and food delivery

LAST MILE DELIVERY OVERVIEW

The majority of households are unoccupied during the postal delivery times

- Failed deliveries increase the CO_2 emissions
- Light duty vehicles
- Electric tricycles
- Drones
- Public transport



COMBINING PASSENGER AND PARCEL TRANSPORT

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Challenges of Integration

- Operational complexity (routing, timing, space constraints)
- Safety and privacy concerns for passengers
- Legal and insurance hurdles
- Balancing delivery efficiency with passenger satisfaction

Opportunity

- Shared infrastructure for transporting goods and people

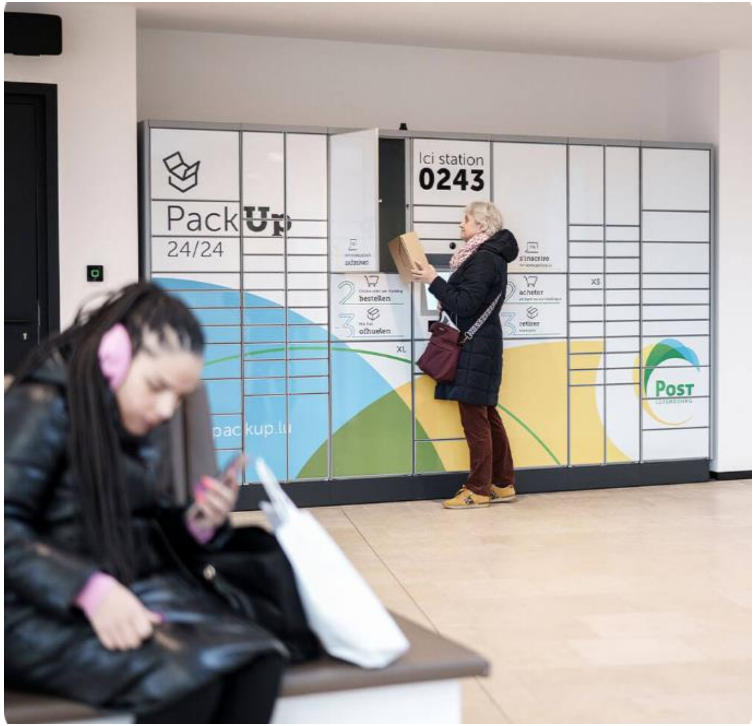
COMBINING PASSENGER AND PARCEL TRANSPORT

- Routing problems
- Lockers
- Delivery by personal cars (light duty vehicles)
- Use of drones/ robots/ public transportation
- Multi-purpose vehicle design (modular seating/storage)
- AI for dynamic routing and load management
- Digital twins and simulation for urban mobility planning
- Policy frameworks supporting multi-use transport

DESCRIPTION OF THE PROBLEM

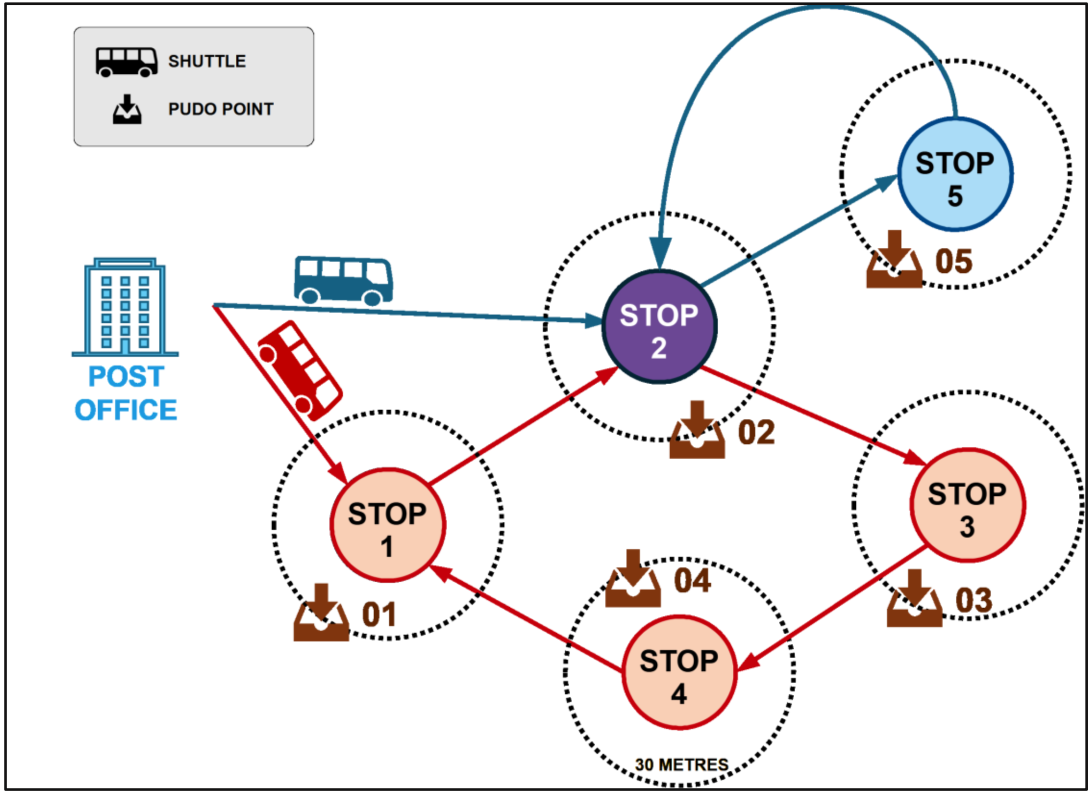
Autonomous shuttles

Pack up stations



DESCRIPTION OF THE PROBLEM

Delivery problem example where two shuttles have different routes with one common stop.



DESCRIPTION OF THE PROBLEM

Entities and Notations

$\{SHUTTLE_1, \ldots, SHUTTLE_N\}$,

$STOPS_i = \{st_{i,1}, st_{i,2}, \ldots, st_{i,s}\}$

$B_i = \{b_{i,1}, b_{i,2}, \ldots, b_{i,M}\}$

Maximum capacity of a Basket (H_j)

$SPACE_i = \{sp_{i,1}, sp_{i,2}, \ldots, sp_{i,s}\}$,

shuttle's capacity S_i, $sp_{i,s} \leq S_i$

$x_{i,j,k}$ indicates if the parcel $p_{i,j,k}$ is included into the delivery batch
where i is the shuttle, j is the basket, and k is the parcel's position in the basket

MATHEMATICAL MODEL

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Maximise:

$$f = \sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{k=1}^{K_{i,j}} [p_{i,j,k} \times x_{i,j,k}] \tag{1}$$

Subject to:

$$\sum_{k=1}^{K_{i,j}} h(p_{i,j,k}) \leq H_j \tag{2}$$

$$Stop(p_{i,j,k}) \in STOPS_i \tag{3}$$

$$\sum_{st=k}^{|STOPS_i|} |b_{i,st}| \leq sp_{i,k}, \ \ k = \{1, 2, \ldots, |STOPS_i|\} \tag{4}$$

Where:

$$p_{i,j,k} = \begin{cases} 1, & \text{if } p_{i,j,k} \in P_T \\ |P_T| + 1, & \text{if } p_{i,j,k} \in P_{SD} \end{cases} \tag{5}$$

$$x_{i,j,k} \in \{0, 1\} \tag{6}$$

DESCRIPTION OF THE PROBLEM

Maximize the number of parcels delivered

Problem
Number of stops
Number of parcels to be delivered the :
- Same day
- Tomorrow

Request
Delivery location = PUDO points
Load

Constraints
Capacity
Priority to same day parcels

PROBLEM INSTANCE

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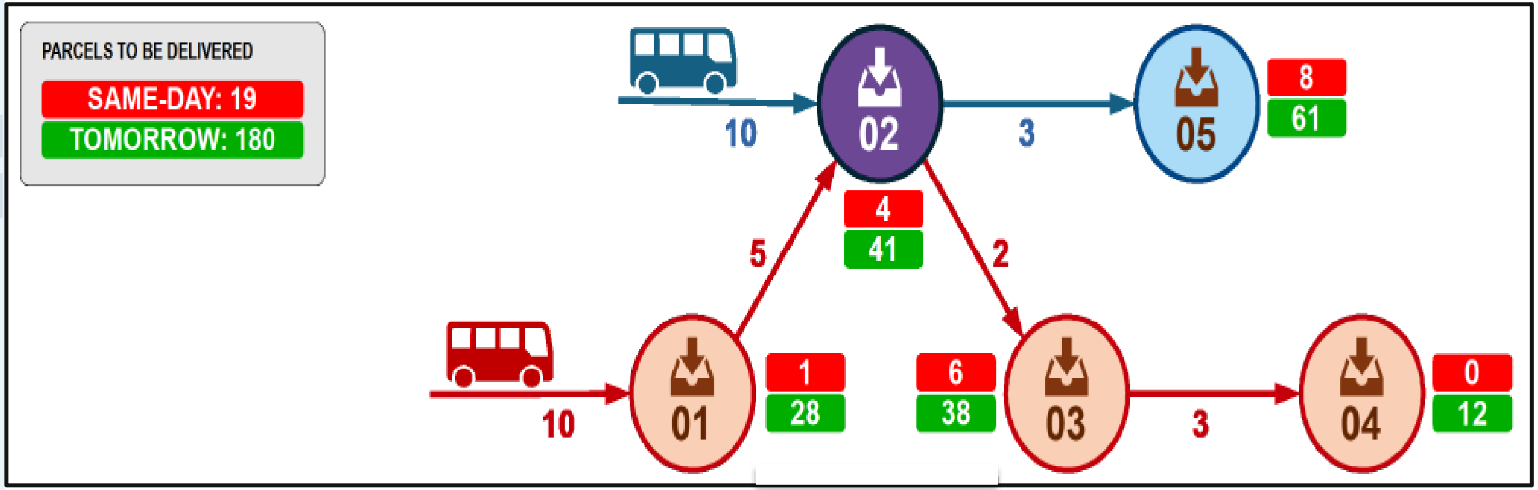
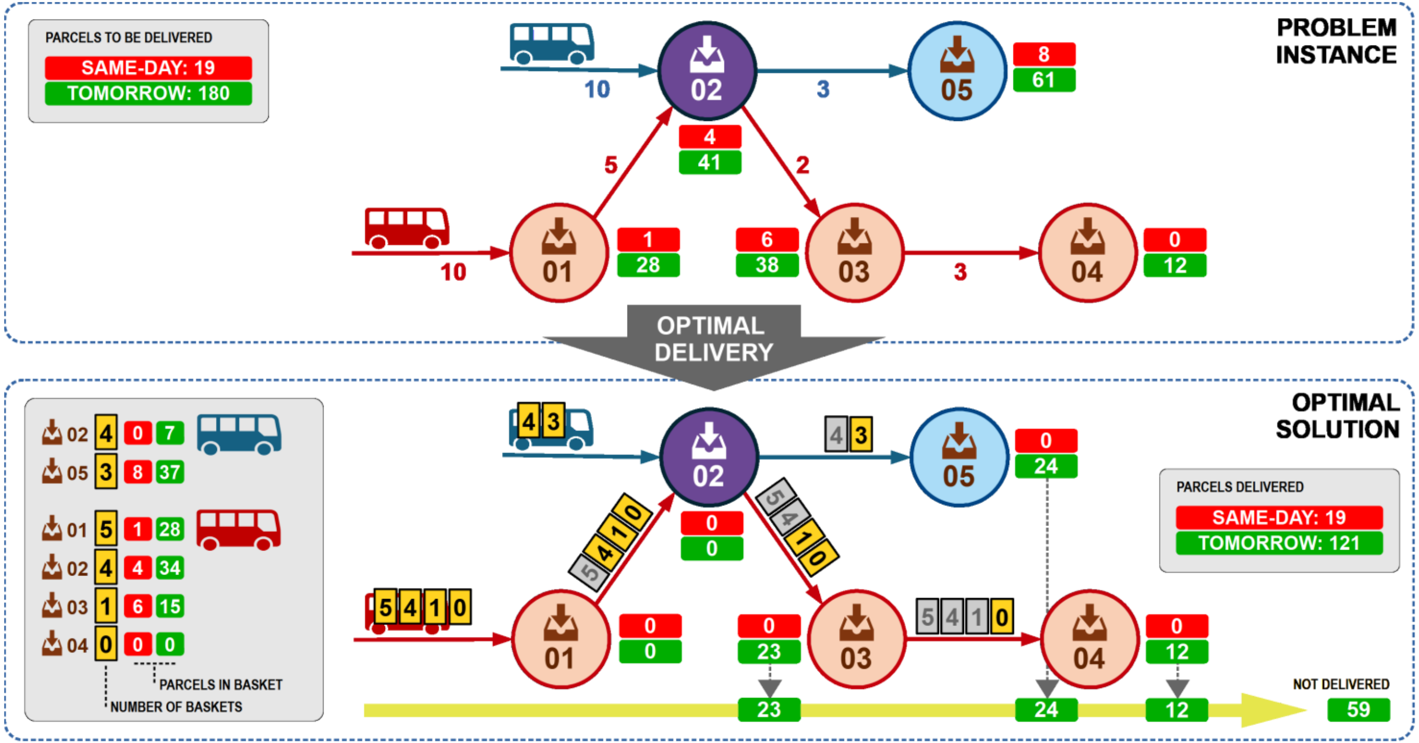


The objective is to maximise the number of parcels delivered the "same-day"

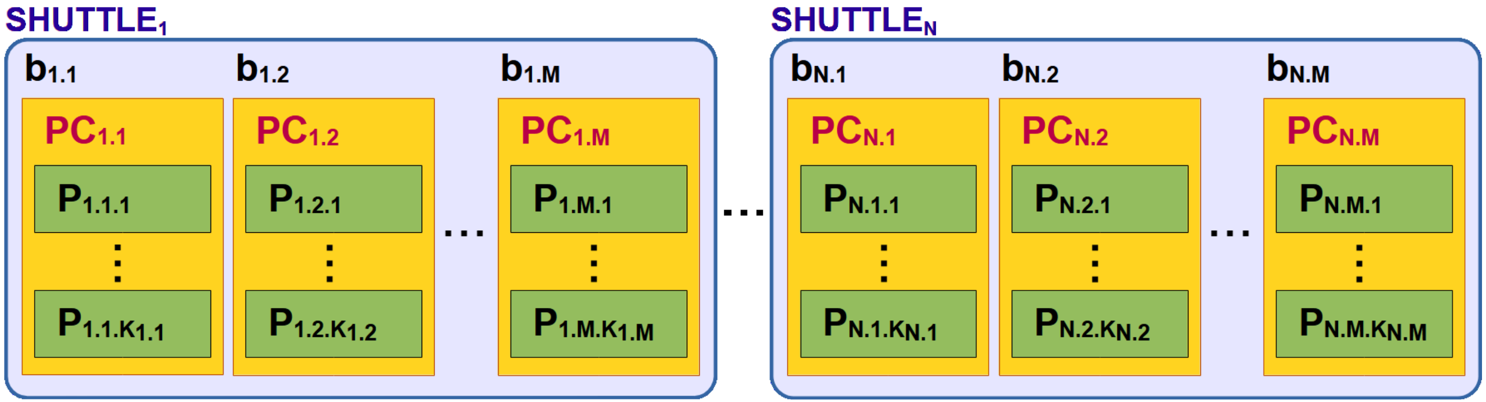
PROBLEM AND SOLUTION REPRESENTATION



A possible optimal solution with detailed delivery plan and results.

SHARE-A-RIDE PROBLEM

Representation of a solution



- N shuttles having up to M baskets.
- Each basket has K parcels to be delivered at the stop having the postal code PC.

SHARE-A-RIDE PROBLEM

Representation of a solution

$$\vec{x} = \{shuttle_1, \ldots, shuttle_i, \ldots, shuttle_N\}$$
$$shuttle_i = \{basket_{i,1}, \ldots, basket_{i,j}, \ldots, basket_{i,M}\}$$
$$basket_{i,j} = \{p_{i,j,1}, \ldots, p_{i,j,k}, \ldots, p_{i,j,K_{i,j}}\}$$
$$basket_{i_j} \in STOPS_i$$
$$p_{i,j,k} \in PARCELS$$

MATHEMATICAL MODEL

Minimisation problem

$$F(\vec{x}) = \Phi R_{SD} + R_T + \xi \tag{12}$$

$$\Phi = |P_{SD}| + 1 \tag{13}$$

$$R_{SD} = |P_{SD}| - |P^{\star}_{SD}| \tag{14}$$

$$R_T = |P_T| - |P^{\star}_T| \tag{15}$$

$$\xi = \begin{cases} \Phi \times |P_{SD}|, & \text{if } \vec{x} \text{ is not viable} \\ 0, & \text{otherwise} \end{cases} \tag{16}$$

$|P^{\star}_{SD}|$ is the number of parcels actually delivered by the proposed solution

ALGORITHMS DEVELOPED

- **Greedy algorithm (GR)**
- **Genetic Algorithm (GA)**
- **Random Search** as a way to assess the validity of the GA and GR

ALGORITHMS DEVELOPED

Pseudocode of the Greedy Algorithm (GR)

```
GR()
P_SD ← Sort(parcels, same-day)
P_T ← Sort(parcels, tomorrow)
sol ← EmptySolution()
{First: add "same-day" parcels}
for all shuttle in sol do
  for all stop in Stops(shuttle) do
    for all p in P_SD do
      if Stop(p) = stop then
        if Fits(baskets(shuttle), p) then
          basket ← basket ∪ {p} {add to basket}
        else if Viable(sol, new_basket) then
          sol[shuttle][new_basket] ← {p} {new}
{Second: complete with "tomorrow" parcels}
for all shuttle in sol do
  for all basket in shuttle do
    for all p in P_T do
      if Stop(p) = Stop(shuttle) then
        if Fits(basket, p) then
          basket ← basket ∪ {p}
{Finally, add new baskets for "tomorrow" if possible}
for all shuttle in sol do
  for all stop in Stops(shuttle) do
    while Viable(sol, new_basket) do
      for all p in P_T do
        if Stop(p) = stop then
          if Fits(new_basket, p) then
            new_basket ← new_basket ∪ {p}
return sol
```

ALGORITHMS DEVELOPED

Genetic algorithm

Pseudocode of the Genetic Algorithm (GA)

$\mathbf{GA}(n_i, p_c, p_m)$
$t \leftarrow 0; \quad n_{ev} \leftarrow 0$
$Q(0) \leftarrow \emptyset$ {Q=auxiliary population}
$P(0) \leftarrow Initialisation(n_i)$ {Pop=population}
while $n_{ev} < MAX\_EVALUATIONS$ **do**
  $Q(t) \leftarrow Selection(P(t))$
  $Q(t) \leftarrow Crossover(Q(t), p_c)$
  $Q(t) \leftarrow Mutation(Q(t), p_m)$
  $Evaluation(Q(t))$
  $P(t+1) \leftarrow Replacement(Q(t), P(t))$
  $t \leftarrow t + 1$
return $Best(P)$

ALGORITHMS DEVELOPED

Genetic algorithm_Selection operator

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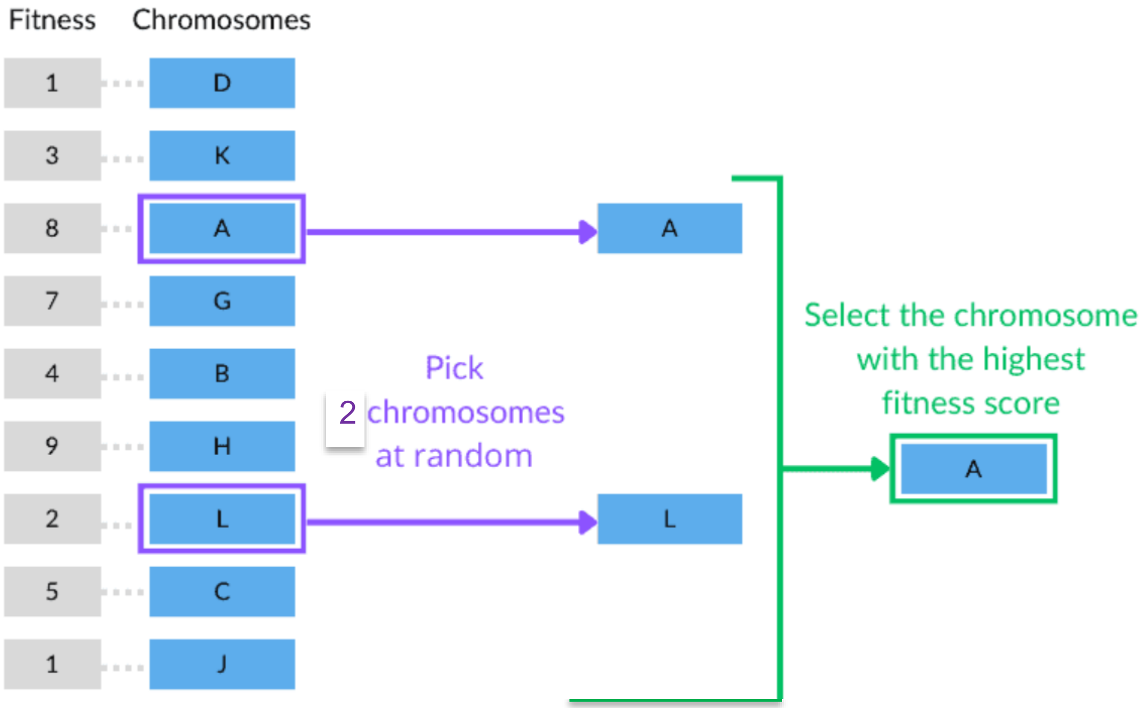
- In a **binary tournament**, two individuals are randomly selected, and the one with the best fitness is chosen.
- **Simplicity:** It's a simple and computationally inexpensive selection method.
- **Commonly Used:** Binary tournament selection is a frequently used technique in genetic algorithms due to its balance of efficiency and effectiveness.
- Larger tournaments tend to favor fitter individuals, leading to faster convergence but potentially reduced diversity.
- This process is repeated until a new population of the desired size is created

ALGORITHMS DEVELOPED

Genetic algorithm_Binary Tournament



ALGORITHMS DEVELOPED

Genetic algorithm_Crossover operator

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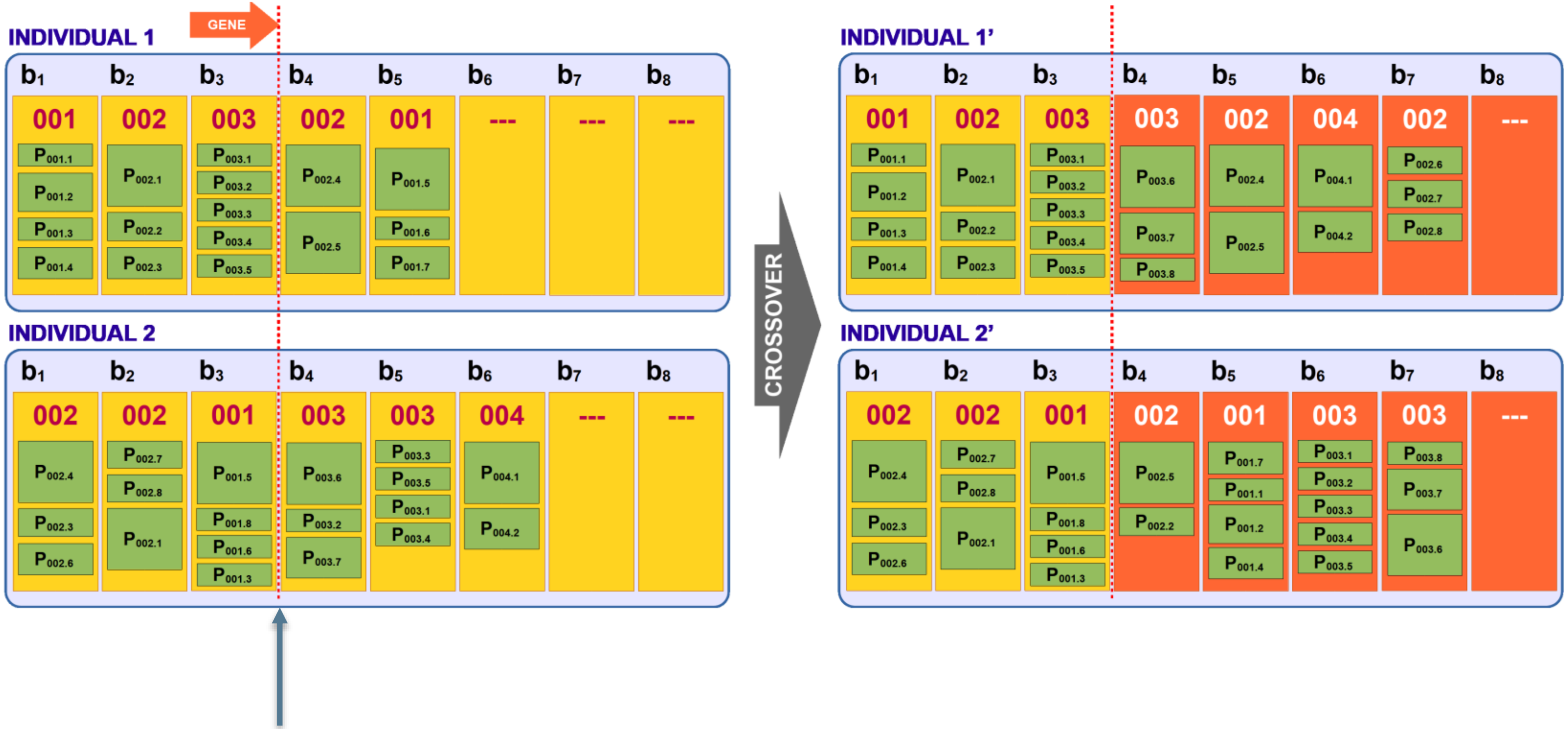
Pseudocode of the Crossover

Crossover$(ind_1, ind_2, cross\_point)$
$gene \leftarrow 0$
for all sh_1,sh_2 **in** ind_1,ind_2 **do**
  for all $basket_1$,$basket_2$ **in** sh_1,sh_2 **do**
    if $gene < cross\_point$ **then**
      $off_1[sh_1][basket_1] \leftarrow ind_1[sh_1][basket_1]$
      $off_2[sh_2][basket_2] \leftarrow ind_2[sh_2][basket_2]$
    else
      if $basket_2 \neq \emptyset$ **and** $Viable(off_1, basket_2)$ **then**
        $off_1[sh_1][basket_1] \leftarrow ind_2[sh_2][basket_2]$
      else
        $off_1[sh_1][basket_1] \leftarrow \emptyset$ {if invalid}
      if $basket_1 \neq \emptyset$ **and** $Viable(off_2, basket_1)$ **then**
        $off_2[sh_2][basket_2] \leftarrow ind_1[sh_1][basket_1]$
      else
        $off_2[sh_2][basket_2] \leftarrow \emptyset$ {if invalid}
    $gene \leftarrow gene + 1$
$off_1 \leftarrow RemoveDuplicatesAndComplete(off_1)$
$off_2 \leftarrow RemoveDuplicatesAndComplete(off_2)$
return off_1,off_2

ALGORITHMS DEVELOPED

Genetic algorithm_Crossover operator



Cut point located at the third gene

ALGORITHMS DEVELOPED

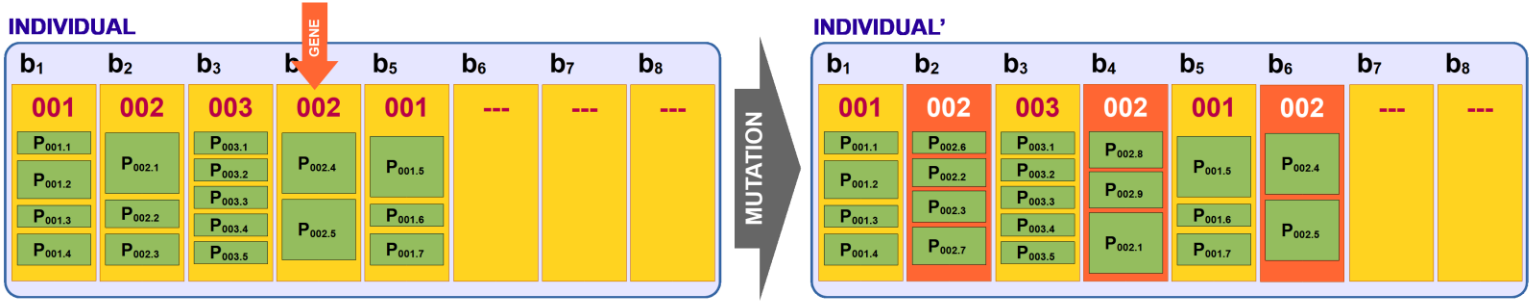
Genetic algorithm_Mutation operator

Pseudocode of the Mutation

```
Mutation(ind, gene)
pc ← PostalCode(ind, gene)
for all shuttle in ind do
  for all basket in shuttle do
    if PostalCode(basket) = pc then
      basket ← ∅ {All baskets for pc are emptied}
parcels ← GetParcels(pc) {All parcels for pc}
found ← false
for all p in parcels do {Assign parcels (sorted)}
  shuttle ← RandShuttle(pc)
  for all basket in RandBasket(shuttle, pc) do
    if Fits(basket, p) then {there is space}
      basket ← basket ∪ {p}
      found ← true
      break
  if not found then {parcel was not added}
    for all basket in RandBasket(shuttle, pc) do
      if basket = ∅ then
        if Viable(ind, basket) then
          ind[shuttle][basket] ← {p} {new basket}
          break
return ind
```

ALGORITHMS DEVELOPED

Genetic algorithm_Mutation operator



Pseudocode of the Random search

Pseudocode of Random Search(RS)

RS()
$best\_sol \leftarrow \emptyset; \quad min\_f \leftarrow 0; \quad n_{ev} \leftarrow 0$
repeat
  $sol \leftarrow RandomSolution()$
  $f \leftarrow Evaluate(sol)$
  if $f \leq min\_f$ **then**
    $best\_sol \leftarrow sol; \quad min\_f \leftarrow f$
  $n_{ev} \leftarrow n_{ev} + 1$
until $n_{ev} = MAX\_EVALUATIONS$
return $best\_sol$

NUMERICAL EXPERIMENTS

Problem instances

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Characteristics of each case study

# shuttles	# instances	# shared stops	# parcels	
			Same-Day	Tomorrow
1	30	0	18 – 40	146 – 193
2	60	0,1	17 – 39	146 – 194
3	90	0,1,2	18 – 47	149 – 189
4	90	0,1,2	17 – 43	155 – 198
5	90	0,1,2	16 – 45	152 – 190

- 360 problem instances in total,30 for one-shuttle scenarios, 60 for two shuttles, and 90 for the rest.
- Each group of 30 instances corresponds to the number of shared stops, i.e. 0, 1, and 2,
- The range of the number parcels was calculated by using a uniform probability distribution
- The number of empty spaces (0 − 14) and parcels' height (1 − 50 cm) are common to all case studies.
- The rest of parameters are:
  - basket capacity (Hi = 100 cm, ∀i),
  - shuttle capacity (Si = 14, ∀i),
  - Number of stops (5 ≤ |STOPSi| ≤ 20).
  - The maximum number of baskets per shuttle (M) corresponds to the shuttle capacity, i.e. M = 14.

NUMERICAL EXPERIMENTS

Problem instances

Hyperparameters of the GA calculated by IRACE

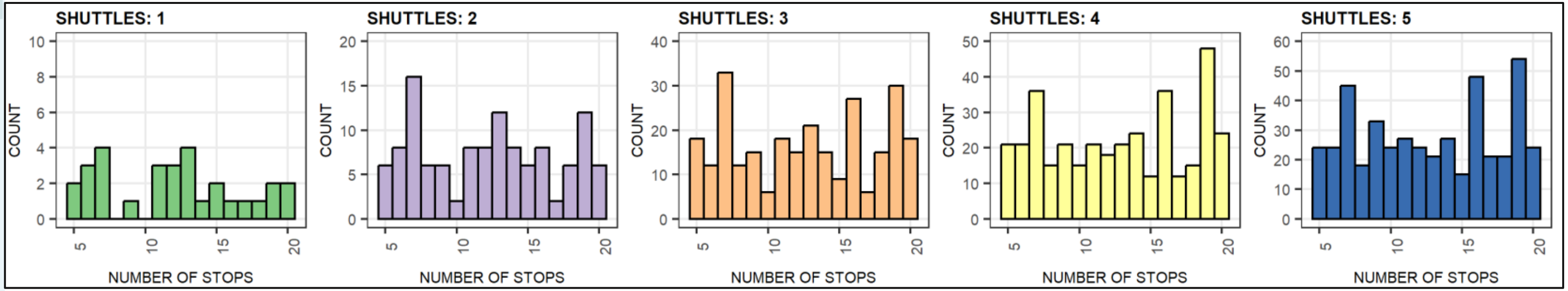
# shuttles	1	2	3	4	5
P_c	0.6000	0.9444	0.7442	0.6233	0.8388
P_m	0.1867	0.1010	0.1492	0.1615	0.1910

- Irace is an implementation of the iterated racing procedure which uses Friedman's non-parametric two-way analysis of variance by ranks
- maximum number of evaluations : 10,000
- Number of individuals: 400 according to the observed algorithm's convergence.
- crossover probability Pc and mutation probability Pm, calculated by performing 2000 experiments per case study with a confidence interval for the elimination test of 0.95.

NUMERICAL EXPERIMENTS

Problem instances

Histograms with number of stops, randomly calculated, used in the scenarios of each case study



NUMERICAL EXPERIMENTS

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Results for the 360 scenarios, best fitness and run time values for 30 runs of RS and GA (GR is one run)

# shuttles	# scenarios	RS		GR		GA		Improvements					
		Avg. fitness	Avg. time (s)	Avg. fitness	Avg. time (s)	Avg. fitness	Avg. time (s)	GA vs. RS			GA vs. GR		
								Min.	Avg.	Max.	Min.	Avg.	Max.
1	30	6338.1	20.0	3262.6	0.001	2853.5	39.9	45.4%	146.4%	503.4%	0.2%	17.7%	62.4%
2	60	5938.5	22.8	3339.3	0.002	2927.6	68.4	35.9%	128.4%	340.0%	0.2%	17.7%	44.0%
3	90	5556.5	25.1	3017.6	0.002	2693.2	69.9	48.2%	146.9%	293.2%	0.2%	15.0%	36.4%
4	90	5305.3	26.7	2758.0	0.002	2429.6	70.4	45.5%	157.5%	426.3%	1.0%	15.1%	48.5%
5	90	5310.5	28.2	2541.7	0.002	1633.3	69.7	66.6%	197.4%	989.1%	0.8%	16.3%	61.7%

Total number of parcels to be delivered by case study and solutions obtained by each optimization algorithm

# shuttles	# scenarios	Parcels		GR			GA		
				Delivered		Not delivered by shuttles	Delivered		Not delivered by shuttles
		Same-Day	Tomorrow	Same-Day	Tomorrow		Same-Day	Tomorrow	
1	30	862	5069	316	469	5146 (86.8%)	386	891	4654 (78.5%)
2	60	1749	10290	635	1230	10174 (84.5%)	773	2280	8986 (74.6%)
3	90	2682	15321	1169	2196	14638 (81.3%)	1330	4016	12657 (70.3%)
4	90	2653	15410	1283	2160	14620 (80.9%)	1443	4355	12265 (67.9%)
5	90	2746	15318	1478	2389	14197 (78.6%)	1589	4878	11597 (64.2%)

NUMERICAL EXPERIMENTS

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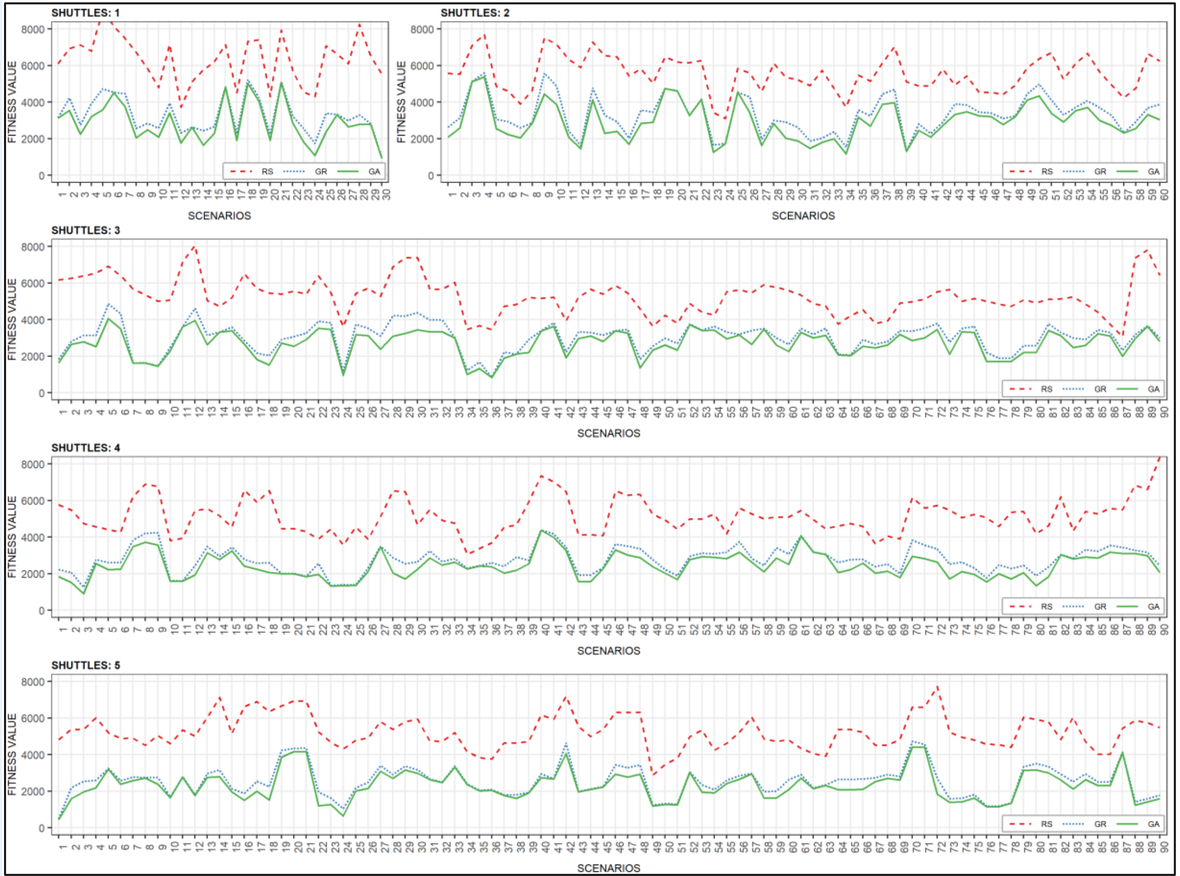
Comparison of the best fitness values for the 360 scenarios, obtained with the Random Search (RS) in red , Greedy (GR) in blue, and Genetic Algorithm (GA) in green.



CONCLUSION

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- Design of two algorithms for last mile parcel delivery using mobility services.
- Greedy algorithm rapidly finds good solutions (hundredths of second)
- Genetic algorithm improves the quality of the solutions but slower
- Adoption of the solution would:
  - reduce the delivery costs
  - improve the road traffic conditions (jams and greenhouse gas emissions)

PERSPECTIVES

- Real tests in Belval and other places
- Real passenger and logistics data
- Explore other operators/ local search algorithms that would be more efficient.
- Hybridise a local search with an evolutionary schema
- Increase convergence of mobility and logistics platforms
- Increase integrated collaboration between public and private agencies

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QUESTIONS ?

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