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# Hazardous Waste Management

## A capacitated multi-vehicle periodic Vehicle Routing Problem to optimize the weekly collection of Healthcare Waste


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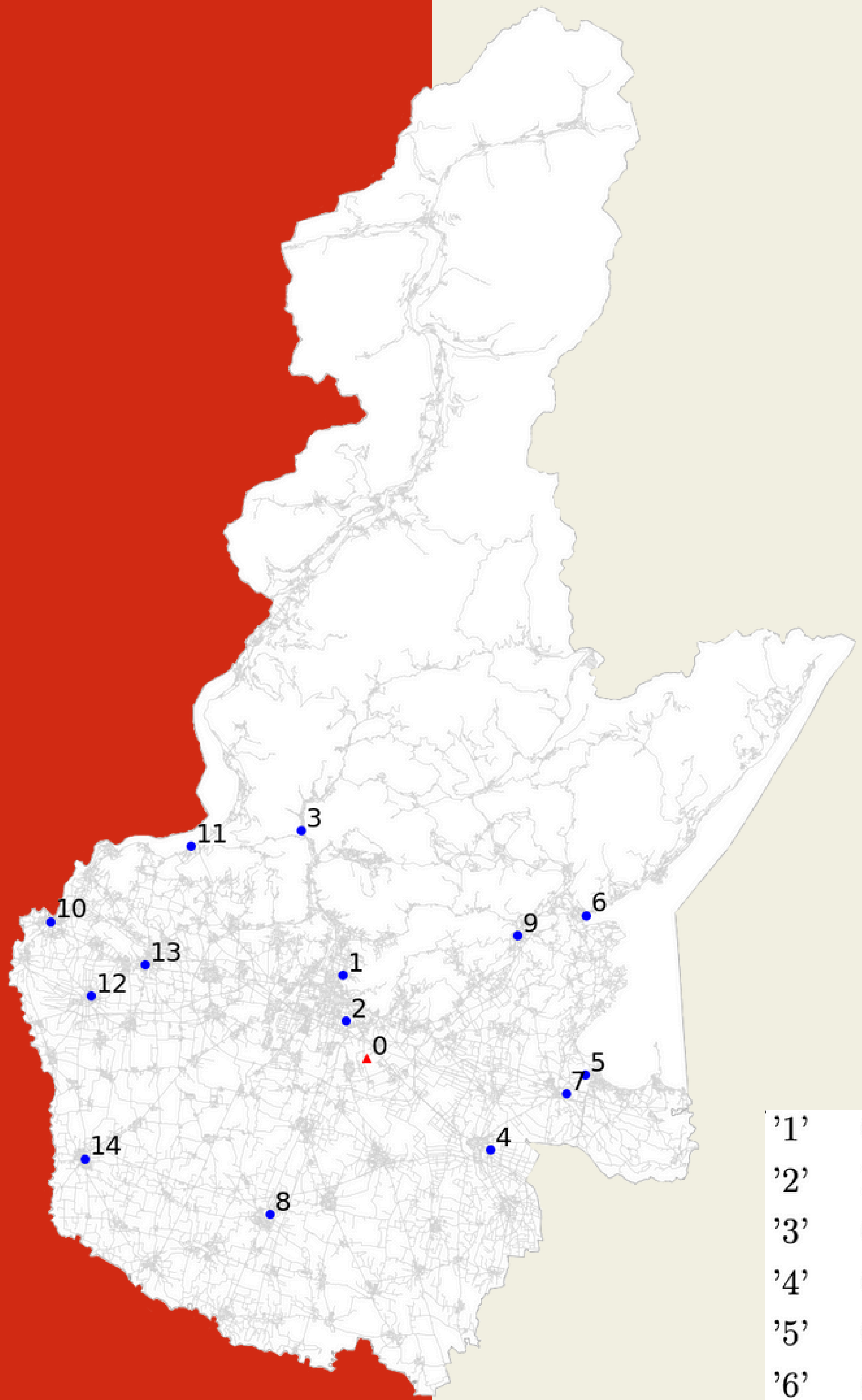
Optimization Methods in Business Analytics

# Agenda




# Problem Description

- 14 hospital facilities in the province of Brescia
- 3 main ASSTs (Brescia, Garda, Franciacorta)
- 1 depot
- Management of hazardous and special waste
- Compliance with ADR regulations

# Objectives

- Minimize travel time and minimize risks
- Optimize weekly collection frequency
- Comply with safety constraints
- Consider road risk factors

| | |
|---|---|
| '1' | Ospedale Civile di Brescia (ASST Brescia), |
| '2' | Poliambulanza, |
| '3' | Ospedale di Gardone Val Trompia(ASST Brescia, |
| '4' | Ospedale di Montichiari (ASST Brescia), |
| '5' | Ospedale di Desenzano del Garda(ASST del Garda), |
| '6' | Ospedale di Salò (ASST del Garda), |
| '7' | Ospedale di Lonato del Garda (ASST del Garda), |
| '8' | Ospedale di Manerbio (ASST Garda), |
| '9' | Ospedale di Gavardo (ASST del Garda), |
| '10' | Ospedale di Palazzolo sull'Oglio (ASST Franciacorta), |
| '11' | Ospedale di Iseo (ASST Franciacorta), |
| '12' | Ospedale di Chiari (ASST Franciacorta), |
| '13' | Ospedale di Rovato (ASST Franciacorta), |
| '14' | Ospedale di Orzinuovi (ASST Franciacorta). |

# Waste Classification and Generation

| TYPE | CATEGORY | CER CODE |
|---|---|---|
| A | Non-toxic, Non-flammable, Non-corrosive Chemical Waste | 18 01 07 |
| B | Toxic, Flammable and/or Corrosive Chemical Waste | 18 01 06 |
| C | Infectious Waste | 18 01 03 |
| D | Special Waste (Including Anatomical Parts and Ashes) | 18 01 02 |
| E | General Healthcare Waste | 18 01 04 |

# Waste Classification and Generation

**Healthcare waste originates from SURGICAL PROCEDURES performed daily and HOSPITAL BEDS occupied daily.**

### Synthetic but informed database

For all the 14 hospital facilities, we collected information about the *number of surgical procedures performed yearly* and *number of hospital beds available* ⁎

### Daily estimations

- Surgical waste estimated using the average number of surgeries per day per hospital.
- Non-surgical waste computed considering only the number of occupied beds daily, obtained thanks to national and regional bed occupancy statistics.

### Definition of a realistic 7-day waste production

Python-based script to simulate waste production over a 7-day horizon while reflecting realistic hospital activity. The simulation is aligned with weekly averages and with Italian National Institute of Health (ISS) findings of 20–40% drop in waste volumes on weekends (due to lower hospital operations).

⁎if data where not available, they were estimated using Ospedale Civile di brescia as a benchmark

# Risk evaluation and cost matrix

we aim to minimize both **risk exposure** and **travel time**

the risk minimization was handled outside the VRP, during the **preparation of the input data.**

travel time minimization represents the **objective function of the VRP**

1. Road segments were penalized based on their proximity to sensitive areas and on road attributes

$$\text{cost} = \begin{cases} \textit{travel time}+ & \text{base travel time,} \\ \textit{travel time} \times \sum \text{risk weight}+ & \text{risk score based on road attributes} \\ \textit{travel time} \times 0.5+ & \text{penalty if proximity to educational facilities} \\ \textit{travel time} \times 0.5 & \text{penalty if proximity to green areas} \end{cases}$$

2. **Dijkstra's algorithm** was applied to the risk-adjusted road network to find the shortest path between all the nodes of the model allowing us to obtain a **risk-aware cost matrix which serves as a proxy for cost.**

# Proximity-based penalization

## How is it applied?

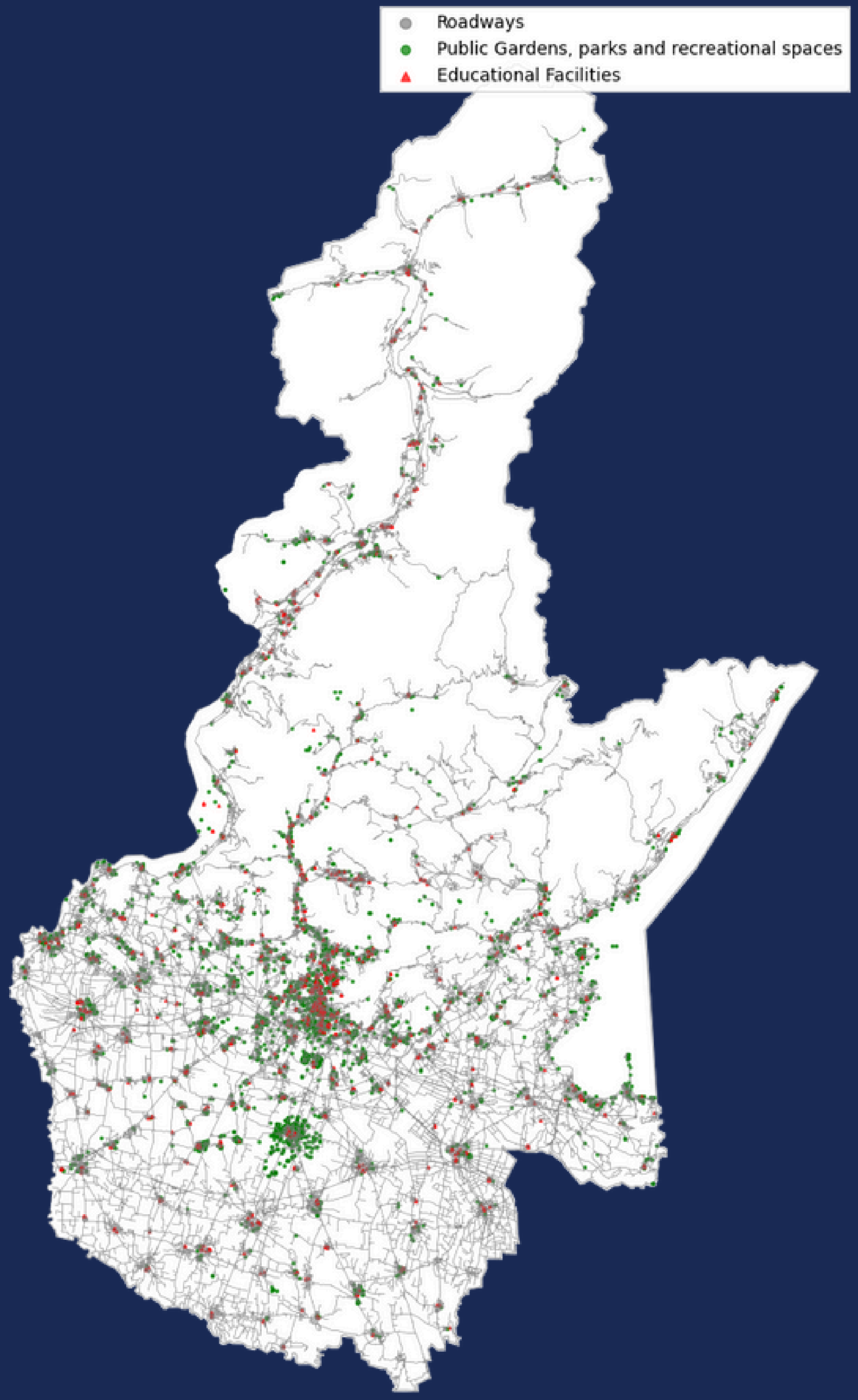
As the transportation involves bio-hazardous wastes and we aim to minimize environmental and social disruption, the model should prioritize routes that avoid sensitive areas such as educational facilities, public gardens and green recreational areas.

First, the **centroids** of these sensitive areas were identified. Then, for each road segment, the distance to the nearest centroid was computed.

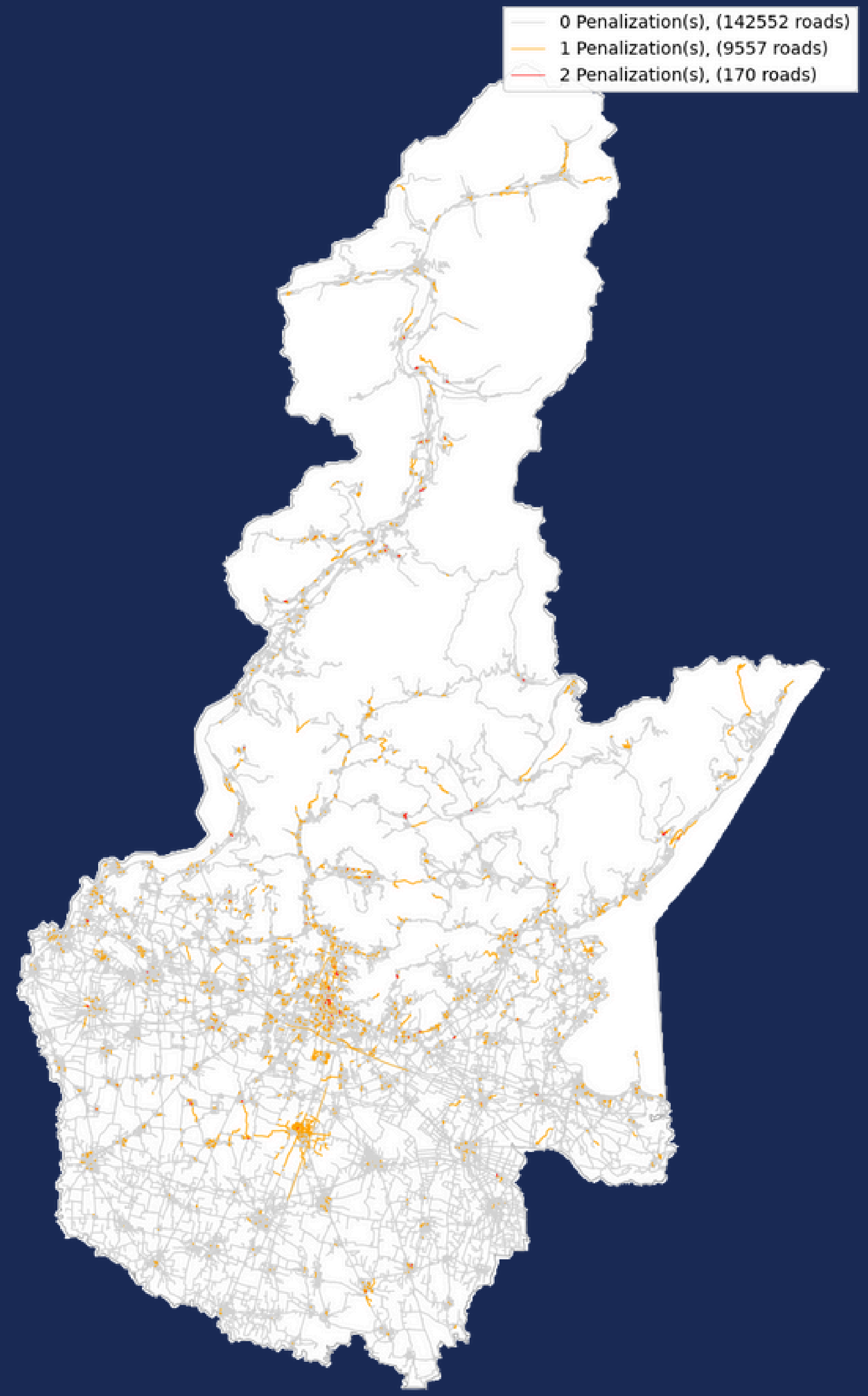
**50 METERS THRESHOLD**

- If a road segment is located within 50 meters of a sensitive area, a proximity penalty is applied.
- If the distance exceeds 50 meters, no penalization is applied.

### Road network and sensitive areas (centroids)




### Penalized roads due to proximity to sensitive areas



# Road attributes based penalization

## How is it applied?

Detailed road attributes extracted from OpenStreetMap and originally represented as a multi-class categorical variable. They were transformed into a binary format, where:

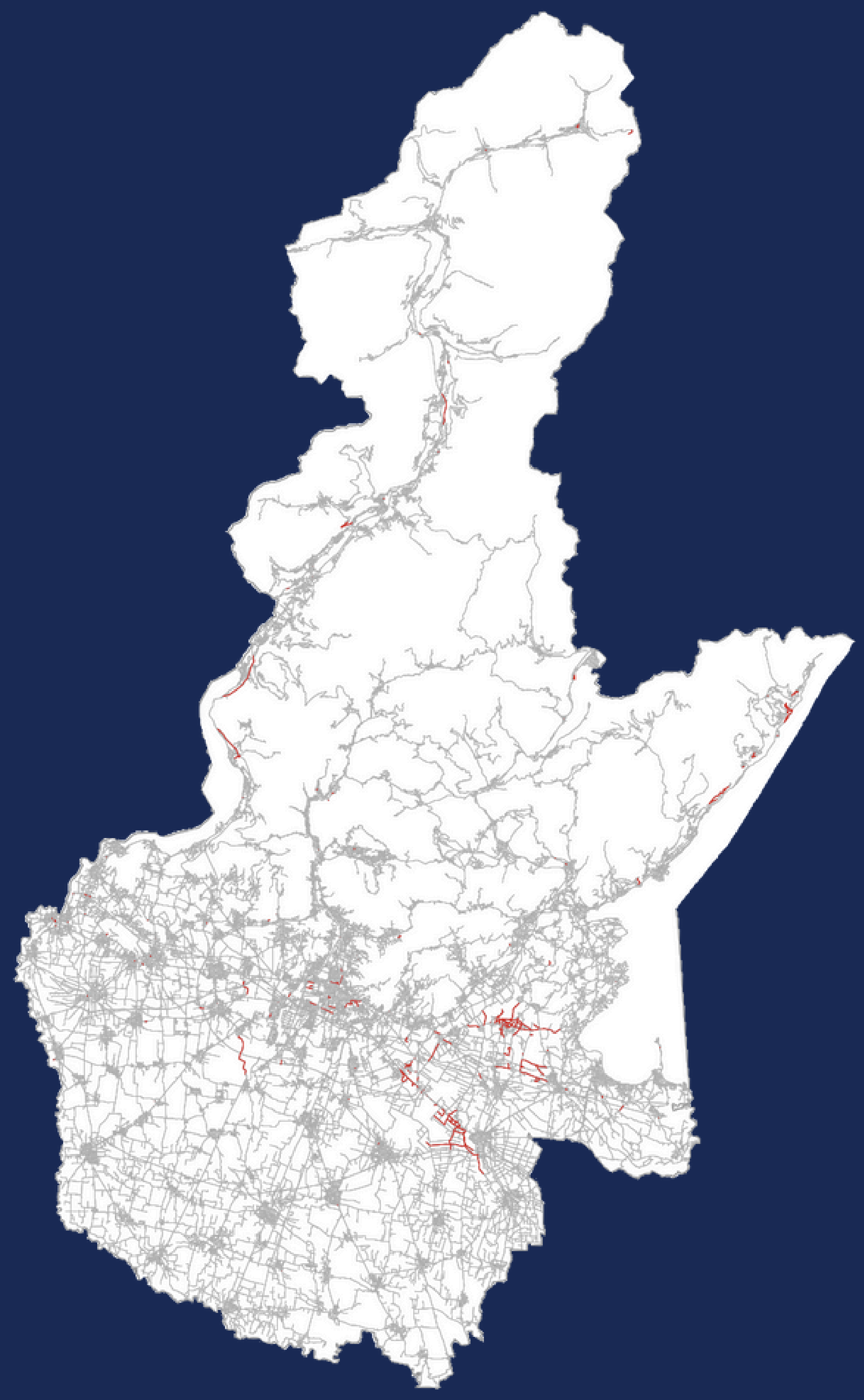
- **0** indicates a safe condition,
- **1** indicates a risky condition.

These weights were normalized so that their sum equals 1, ensuring the resulting scores are comparable across different segments

$$\text{risk\_weights} = \begin{cases} \text{'risk\_surface'} & 0.15, \\ \text{'risk\_lit'} & 0.05, \\ \text{'risk\_service'} & 0.10, \\ \text{'risk\_smoothness'} & 0.10, \\ \text{'risk\_tracktype'} & 0.05, \\ \text{'risk\_highway'} & 0.15, \\ \text{'risk\_lanes'} & 0.10, \\ \text{'risk\_width'} & 0.10, \\ \text{'risk\_bridge'} & 0.05, \\ \text{'risk\_access'} & 0.05, \\ \text{'risk\_tunnel'} & 0.10. \end{cases}$$

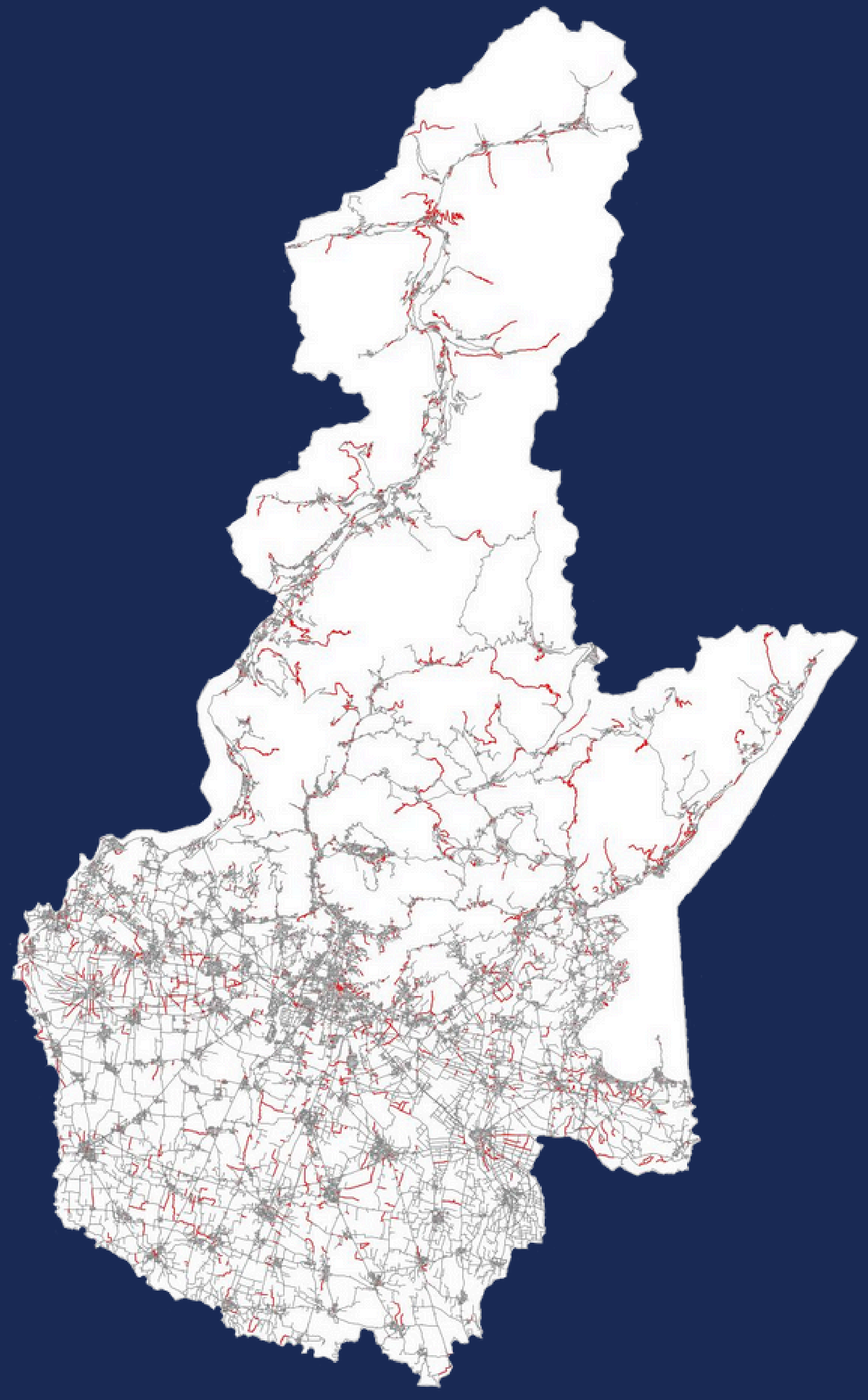
**Road that cannot be included in the model by law**

(total of 1380 road segments )



**Roads with a risk score higher than 25%**

(total of 5035 road segments)



# Risk evaluation and cost matrix

## To sum up:

A total of **152,312** road segments were extracted from OpenStreetMap.

Of these:

- **9,571** segments (**0,062**%) received one proximity penalization, meaning they are located within 50 meters of either a school or a green/recreational area.
- **170** segments (0,001%) are in proximity to both schools and green areas, and therefore received two penalizations.
- **1,380** road segments (**0.01%**) were excluded from the application of Dijkstra’s algorithm (due to access restrictions or non-drivable paths).

# Cost matrix - input for VRP

**ASYMMETRIC**

Because it is a realistic representation of urban road networks where the same road might not be travelled in the opposite direction

**EXPRESSED IN SECONDS**

Because it is obtained by adding penalities to the travel time (seconds)

| nodes | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **0** | 0 | 740.35 | 481.26 | 1875.63 | 1216.26 | 1371.77 |
| **1** | 750.45 | 0 | 423.34 | 1154.02 | 1765.55 | 1666.02 |
| **2** | 486.51 | 442.32 | 0 | 1584.52 | 1419.13 | 1319.60 |
| **3** | 1876.02 | 1125.57 | 1548.91 | 0 | 2771.09 | 2695.37 |
| **4** | 1286.32 | 1722.75 | 1463.66 | 2787.65 | 0 | 1028.04 |
| **5** | 1310.64 | 1673.13 | 1305.84 | 2624.68 | 1022.02 | 0 |
| **6** | 1522.47 | 1919.97 | 1660.87 | 2904.10 | 2019.10 | 1338.31 |
| **7** | 1325.35 | 1687.84 | 1320.55 | 2639.38 | 678.36 | 499.92 |
| **8** | 1237.49 | 1406.96 | 1039.67 | 2460.43 | 1710.84 | 1847.05 |
| **9** | 1165.81 | 1563.30 | 1304.21 | 2530.77 | 1674.86 | 1558.29 |
| **10** | 1775.00 | 1701.05 | 1567.06 | 2070.48 | 2543.03 | 2355.82 |
| **11** | 1467.10 | 1453.52 | 1259.15 | 1066.19 | 2381.41 | 2280.04 |
| **12** | 1505.15 | 1582.42 | 1388.05 | 2050.94 | 2062.63 | 2246.16 |
| **13** | 1335.50 | 1261.55 | 1127.56 | 1630.99 | 2030.03 | 1916.32 |
| **14** | 2066.20 | 2313.04 | 2191.28 | 2909.72 | 2623.68 | 3009.92 |

# CVRP

**PARAMETERS:**

- $V = \{0, 1, \ldots . n\}$: set of vertices, where vertex 0 represents the depot and $\{1, \ldots . , n\}$ represents the customers
- $c_{ij}$ : cost (travel time) from vertex *i* to vertex *j*, for all $i, j \in V$
- $Q$ : vehicle capacity
- $q_i$ :demand of costumer *i*, for all
- $K$ :set of vehicles $i \in \{1, \ldots . , n\}$

**DECISION VARIABLES:**

- $x_{ij}^k \in \{0, 1\}$ : binary variable that equals 1 if vehicle *k* travels directly from vertex *i* to vertex *j*, and 0 otherwise, for all $i, j \in V$ and $k \in K$
- $u_i^k$ : auxiliary variable representing the load of the vehicle *k* after serving customer *i*, for all $i \in \{1, \ldots . , n\}$

# CVRP

## OBJECTIVE FUNCTION:

$$\textbf{Minimize the total cost: } \sum_{k \in K} \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij}^k$$

## SUBJECT TO:

- Each costumer is visited once: $$\sum_{k \in K} \sum_{j \in V} x_{ij}^k = 1, \quad \forall i \in \{1, \ldots, n\}$$
- Each vehicle leaves the depot: $$\sum_{j \in V} x_{\text{DepotEntry},j}^k = 1, \quad \forall k \in K$$
- Each vehicle returns to the depot: $$\sum_{i \in V} x_{i,\text{DepotExit}}^k = 1, \quad \forall k \in K$$
- Flow conservation: $$\sum_{i \in V} x_{ij}^k = \sum_{i \in V} x_{ji}^k, \quad \forall j \in \{1, \ldots, n\}, \forall k \in K$$
- Subtour elimination and capacity constraint: $$u_i - u_j + Q x_{ij}^k \leq Q - q_j, \quad \forall i, j \in \{1, \ldots, n\}, \ \forall k \in K, \ i \neq j$$
- Load limits: $$q_i \leq u_i \leq Q, \quad \forall i \in \{1, \ldots, n\}$$
- Binary decision variables: $$x_{ij}^k \in \{0, 1\}, \quad \forall i, j \in V, \forall k \in K$$

# External operational logic for Waste Type "B"

| Waste Category | A | B | C | D | E |
|---|---|---|---|---|---|
| A | | ✗ | ✓ | ✗ | ✓ |
| B | ✗ | | ✗ | ✗ | ✗ |
| C | ✓ | ✗ | | ✗ | ✓ |
| D | ✗ | ✗ | ✗ | | ✗ |
| E | ✓ | ✗ | ✓ | ✗ | |

Due to incompatibilities between waste categories, we modeled and solved a ***separate VRP model*** for ***each day*** of the week and **for each waste type group** (ACE, B, and D).

A dedicated VRP for "A", "C", and "E" waste (which can be grouped together) served by 3 vehicles, each with a capacity of 3200 kg);

a dedicated VRP for type "D" waste, served by a refrigerated vehicle with apacity 3900 kg)

a dedicated VRP for type "B" waste, served by a vehicle with capacity 1600 kg).

# External operational logic for Waste Type “B”

**CONDITIONAL COLLECTION**

Due to the relatively small quantity typically generated, for type B waste, collection does not need to occur daily, but **only if the total demand exceeds a predetermined threshold** (> **200kg**)

$$\sum i \in V q_i^{(B)}(t) + r_i^{(B)}(t) > \theta_B = 200 \text{ kg} \longrightarrow$$

trigger for the VRP on day *t*

where:

$q_i^{(B)}(t)$ kg of waste “B” produced on day *t* by facility *i*

$r_i^{(B)}(t)$ kg of waste “B ” not collected in previous days and accumulated at node *i* and computed recursively based on the collection history

$$r_i^{(B)}(t) = r_i^{(B)}(t-1) + q_i^{(B)}(t-1)$$

# Results

| Day | Waste Type | Vehicles Used | Travel Time |
|---|---|---|---|
| Monday | ACE | 3 | 04h 39m |
| Monday | B | 0 | — |
| Monday | D | 1 | 04h 02m |
| Tuesday | ACE | 3 | 04h 39m |
| Tuesday | B | 1 | 04h 02m |
| Tuesday | D | 1 | 04h 02m |
| Wednesday | ACE | 3 | 04h 39m |
| Wednesday | B | 0 | — |
| Wednesday | D | 1 | 04h 02m |
| Thursday | ACE | 3 | 04h 39m |
| Thursday | B | 1 | 04h 02m |
| Thursday | D | 1 | 04h 02m |
| Friday | ACE | 3 | 04h 39m |
| Friday | B | 0 | — |
| Friday | D | 1 | 04h 02m |
| Saturday | ACE | 3 | 04h 27m |
| Saturday | B | 0 | — |
| Saturday | D | 1 | 04h 02m |
| Sunday | ACE | 3 | 04h 27m |
| Sunday | B | 0 | — |
| Sunday | D | 1 | 04h 02m |

Waste Types A, C, and E:

- Collected daily using 3 vehicles.
- Maximum daily travel time: 4h 39m
  Shortest on weekends: 4h 27m

Waste Type B:

- Collected only on Tuesdays and Thursdays.
- Triggered by an accumulation rule requiring 200 kg before dispatch.

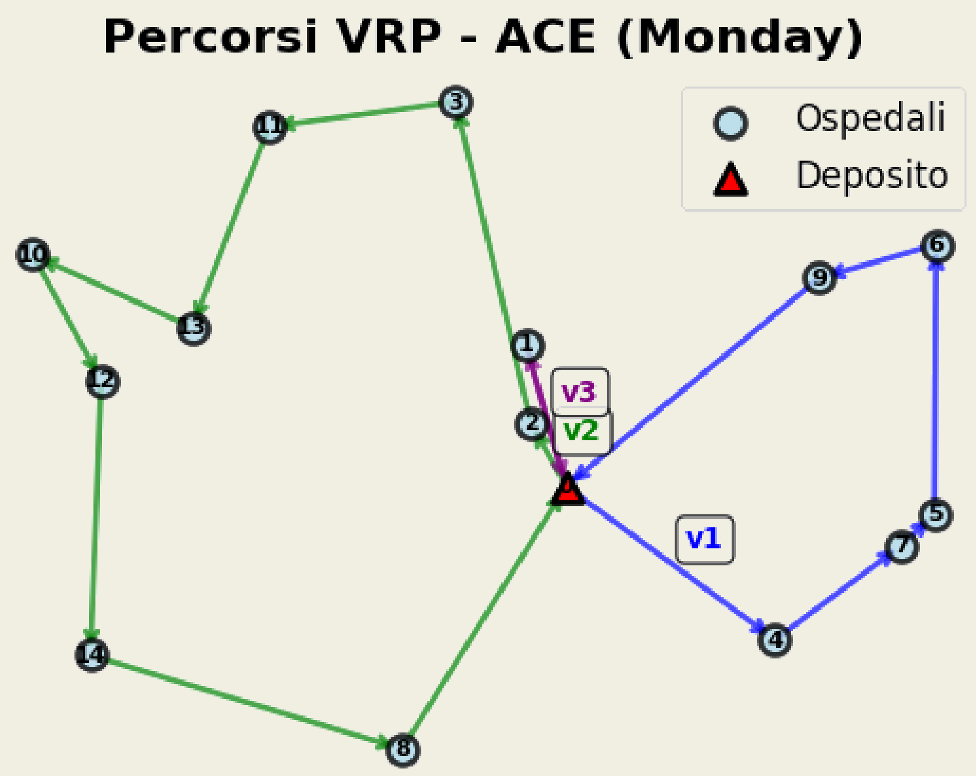
Waste Type D:

- Collected daily by 1 refrigerated vehicle.
- Travel time is consistent at around 4h 2m per day.

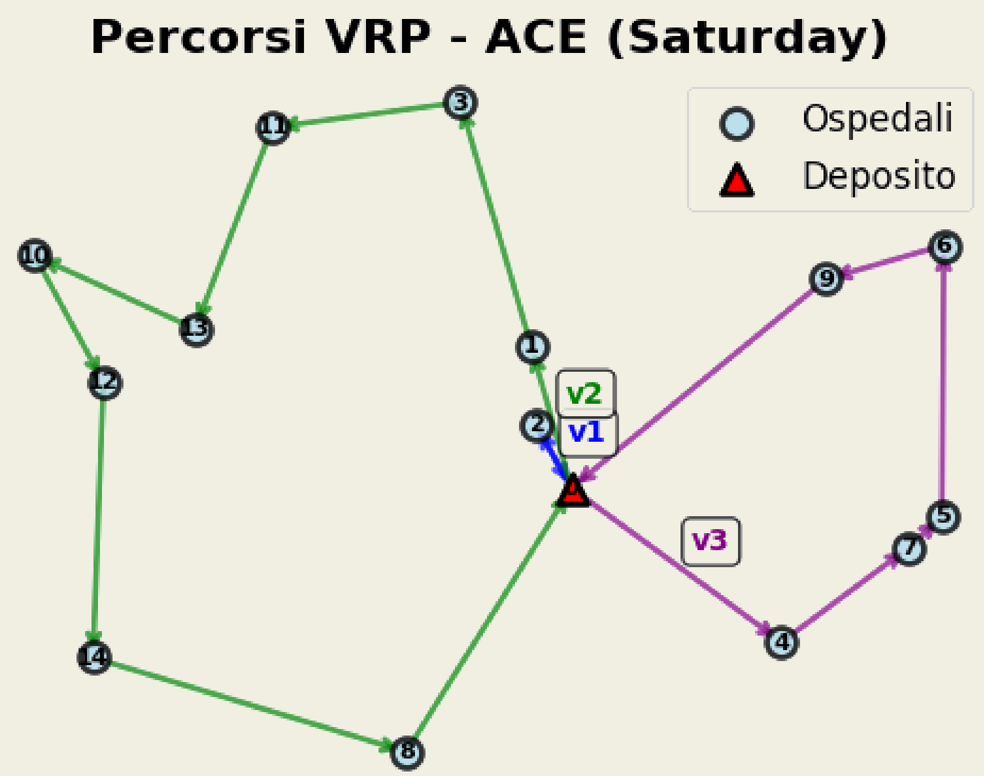
# Results - Vehicles routes

### Vehicles routes for types A,C and E

The key difference between weekdays and weekends lies in the routing for node 1

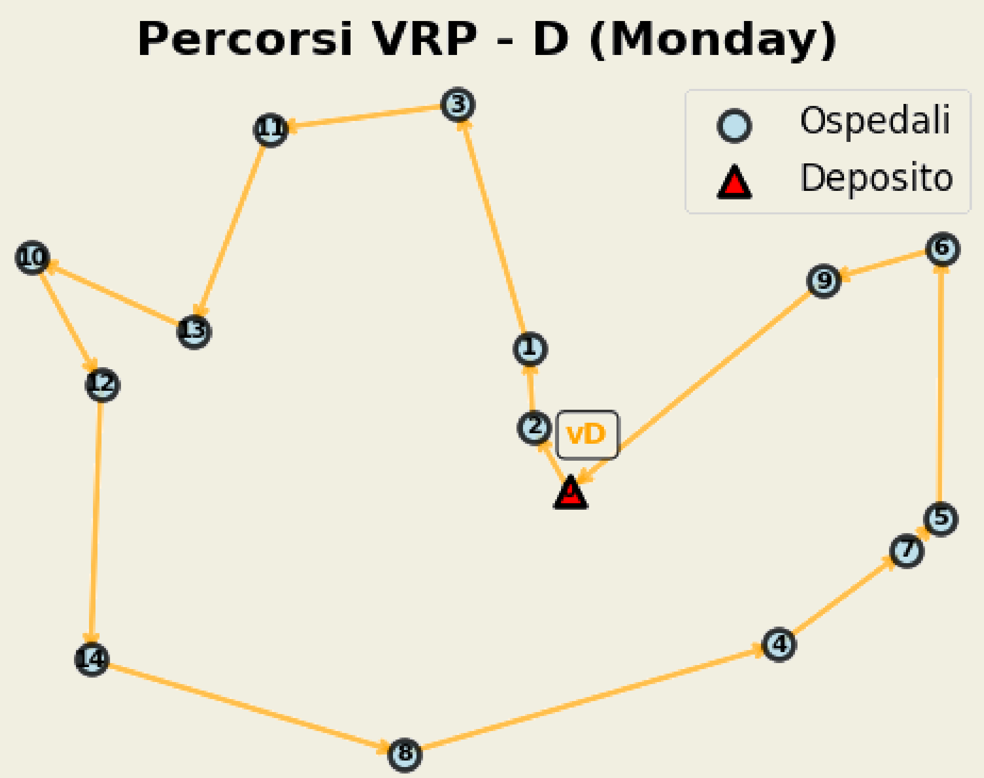



During weekday




During weekend

### Vehicles routes for types B and D



# Limitations and conclusions

Despite the structured methodology, several limitations affect the overall real-world representativeness and applicability of the model - from input preparation to model application.

### LACK OF DATA

- Complete data was not available for every facility; missing values were estimated using a benchmark hospital.
- It was assumed that all hospitals operate in comparable ways, which may not reflect real-world variability in services and capacities.
- The road network data and attributes extracted from OpenStreetMap was extensive, but its accuracy and update frequency were assumed rather than verified.

### SIMPLIFICATION

- Penalty for proximity to schools and parks of 50 m was applied as a straight-line buffer, not accounting for actual road connectivity or intersections.
- The penalty was uniformly applied to the entire road segment in the dataset, even when only a small portion was near a sensitive area.
- Risk exposure was managed externally and not integrated directly into the VRP model.
- Some ADR-related constraints were approximated or handled outside the core optimization.

### MODEL IMPROVEMENT

- Integrate historical accident records and real-time traffic conditions into the risk assessment process for more dynamic and context-aware routing.
- Develop a weekly optimization model (instead of day-by-day) that modulates the number of vehicles and routes based on total weekly demand.
- Implement IoT sensors for continuous waste monitoring and real-time adjustment of collection routes and schedules.

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# Thank you for your attention!


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Optimization Methods in
Business Analytics