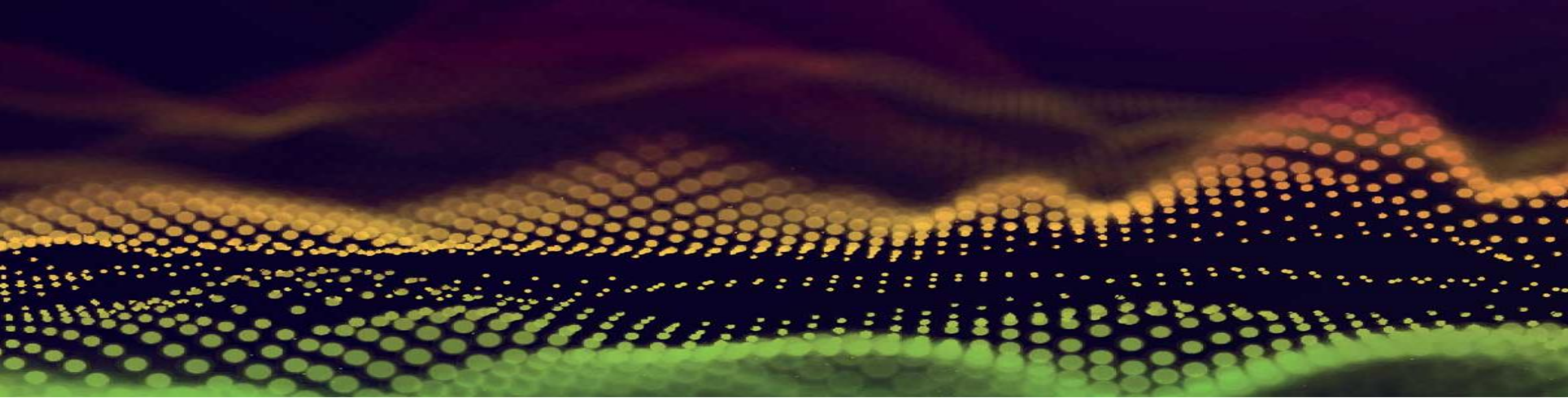

GIS-based Facility Location Analysis for the Public and Private Sectors

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Location Analysis: where should it be?

- Early prehistoric times
  - determining the best location for hunting food, harvesting natural resources, etc.
- Location: important for the success of a private- or public-sector organization
  - Private sector: coffee shop, factories, retail stores
  - Public sector: schools, hospitals, libraries, fire stations, and emergency response services

More Examples …

- What is the minimum number of fire stations (and where should they be located) necessary to cover 90 percent of building fires within 4 minutes of a call for service?
- Where should the manufacturing plant be located to minimize overall transportation costs?
- Glasgow city council wishes to close 11 of their existing 148 primary schools. Which schools should be closed?

Think about locating a retail store:

- Objective: to pick the site which will maximize economic return
- Return is affected by:
  - number of potential customers within market area
  - accessibility of the site (e.g. is it on a main street? is it possible to turn left into the site?)
  - visibility, signage, appearance
  - cost of site and construction

Combinations and Complexity

- Number of unique combinations for selecting *p* items from *n* total items

$$\binom{n}{p} = \frac{n!}{(n-p)!\,p!}$$

- Glasgow public schools wishes to close 11 of their existing 148 primary schools. Which schools should be closed?

$$\binom{148}{11} = \frac{148!}{137!11!} = 1.2775329\text{e+}16$$

Outline

1. Optimization Models
2. Classic Facility Location Models
   - *p*-Median Problem (PMP)
   - Location Set Covering Problem (LSCP)
   - Maximal Covering Location Problem (MCLP)
3. Location-allocation Analysis in ArcGIS
4. Overview of the Tutorial

1. Optimization Models

Optimization Models

- Have a goal or objective specified as a mathematical function
  - Maximization or minimization of an objective function
- Also have restrictions or constraints expressed as mathematical functions
  - Problem subject to maintaining constraining conditions
- Decision to make
  - decision variables

Max $g(x)$

Subject to $f_i(x) \leq b_i$

x conditions

x

2. Classic Facility Location Models

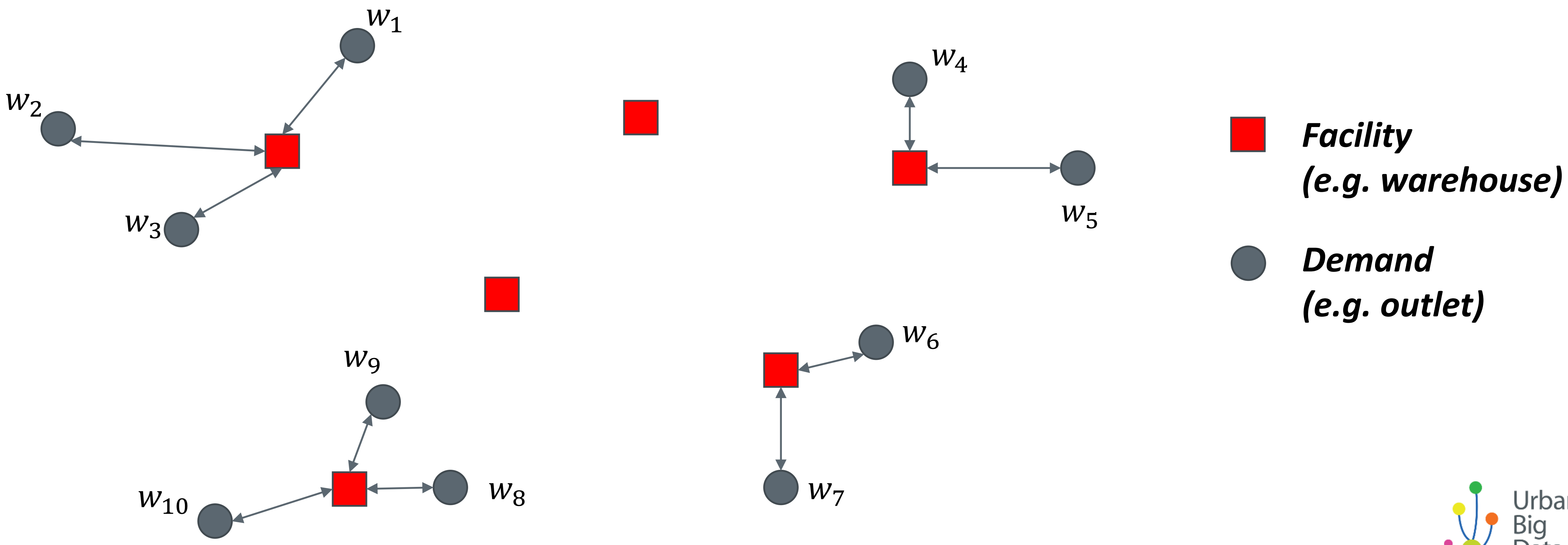
p-Median Problem (PMP)

Location Set Covering Problem (LSCP)

Maximal Covering Location Problem (MCLP)

p-Median Problem (PMP)

- Locate a multiple number of facilities and allocate the demand served by these facilities so that the system is as efficient as possible.



p-Median Problem (PMP):

Mathematical Representation

Notation

- i = index of demand areas
- j = index of potential facility locations
- d_{ij} = shortest distance or travel time from demand area i to potential facility j
- w_i = amount of demand in area i.
- p = number of facilities to be located

Decision Variables

- $Y_j = \begin{cases} 1 \text{ if potential facility } j \text{ is located} \\ 0 \text{ otherwise} \end{cases}$
- $X_{ij} = \begin{cases} 1 \text{ if demand } i \text{ is served by facility } j \\ 0 \text{ otherwise} \end{cases}$

Minimize $\sum_i \sum_j w_i d_{ij} X_{ij}$

The system efficiency measure

Subject to

(1) $\sum_j X_{ij} = 1 \quad \forall i$

Each demand area is to be served by exact one facility

(2) $X_{ij} \leq Y_j \quad \forall i, j$

No allocation occurs unless a facility is sited

(3) $\sum_j Y_j = p$

Totally *p* facilities are to be located

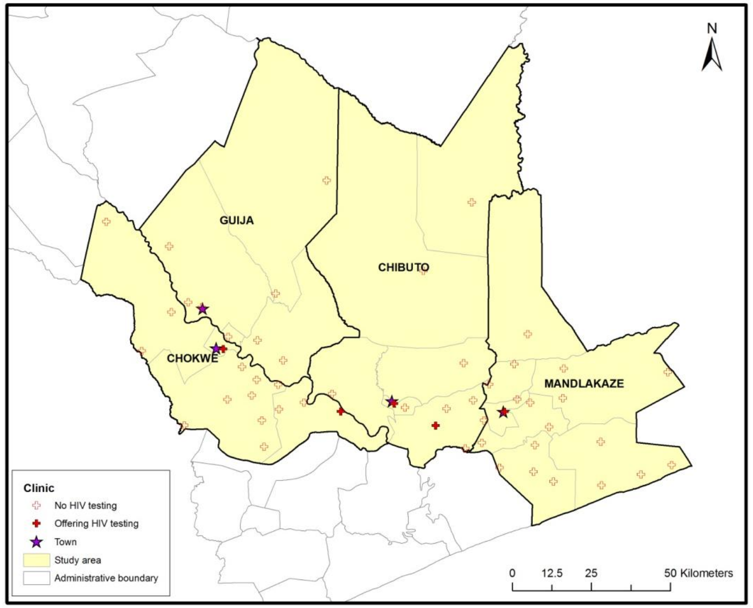
(4) $X_{ij} = \{0,1\} \quad \forall i, j$

$Y_j = \{0,1\} \quad \forall j$

Integer requirements

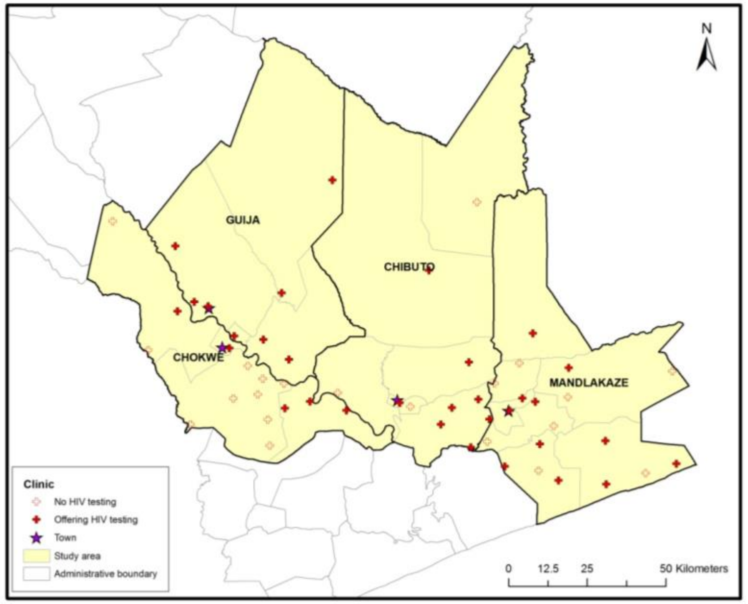
Example: optimizing healthcare facilities and resource allocation in Gaza, Mozambique

Spatial configuration of HIV testing services



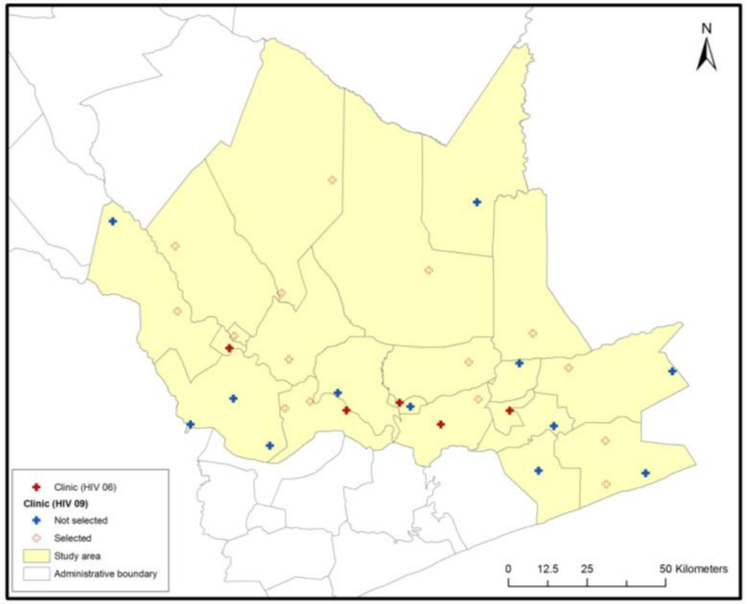
2006 (5)

Average travel distance: 17.7 *km*



2009 (32)

Average travel distance: 6.3 *km*



PMP

Average travel distance: 4.7 *km*

Yao, J., & Murray, A. T. (2014). Locational effectiveness of clinics providing sexual and reproductive health services to women in rural Mozambique. *International Regional Science Review*, 37(2), 172-193.

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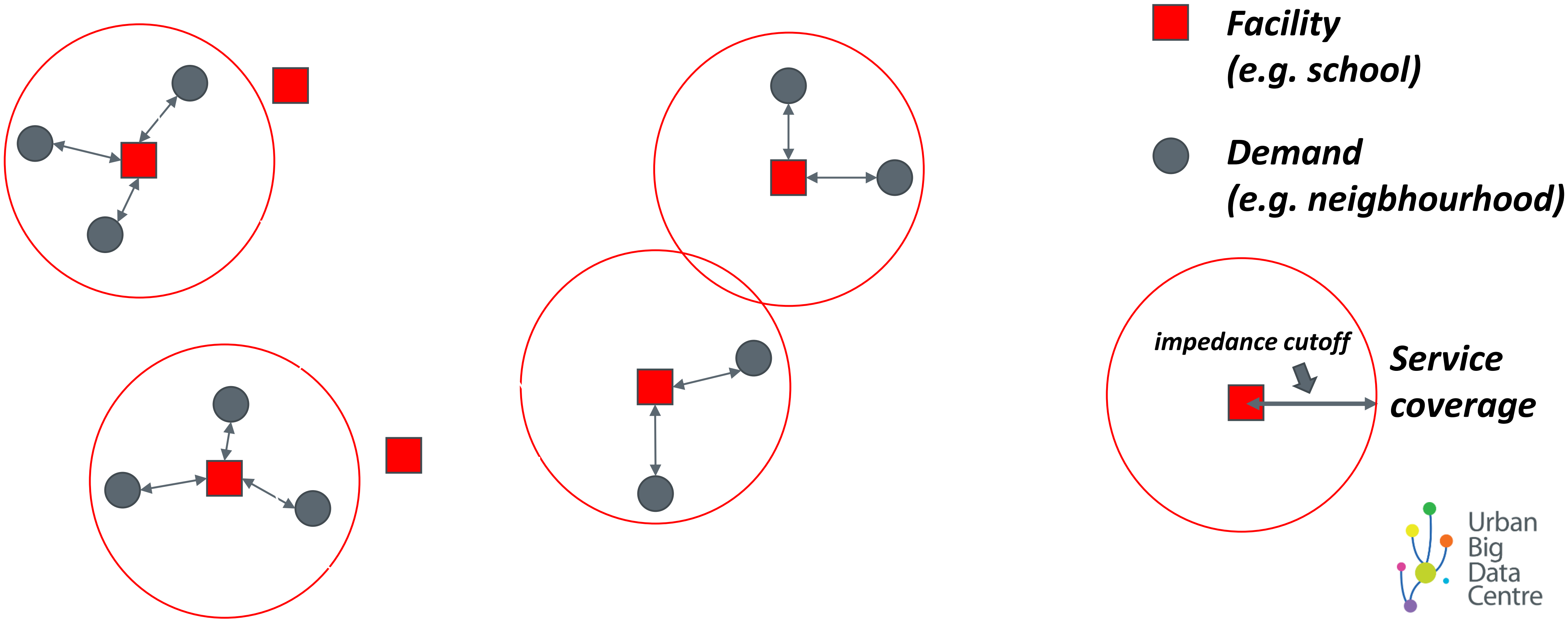
Location Set Covering Problem (LSCP)

- Find the minimum number of facilities and their locations such that all neighborhoods are covered within the maximal distance or time standard.



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Location Set Covering Problem (LSCP)

Mathematical Representation

Notation

- i = index of demand areas
- j = index of potential facility locations
- $a_{ij} = \begin{cases} 1 \text{ if area } i \text{ is suitably servied by a potential facility at site } j \\ 0 \text{ otherwise} \end{cases}$.
- $N_i = \{j | a_{ij} = 1\}$

Decision Variables

- $X_j = \begin{cases} 1 \text{ if potential facility } j \text{ is located} \\ 0 \text{ otherwise} \end{cases}$

Minimize $\sum_j X_j$

Subject to

(1) $\sum_{j \in N_i} X_j \geq 1 \quad \forall i$

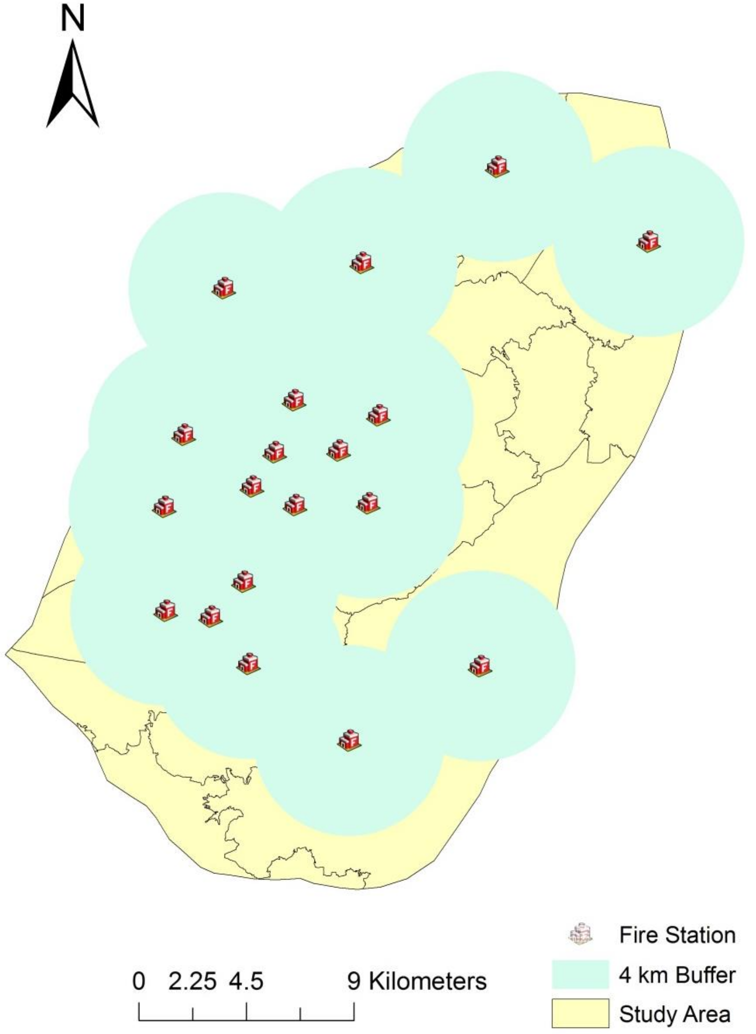
Ensure each demand area provided suitable coverage

(2) $X_j = \{0,1\} \quad \forall j$

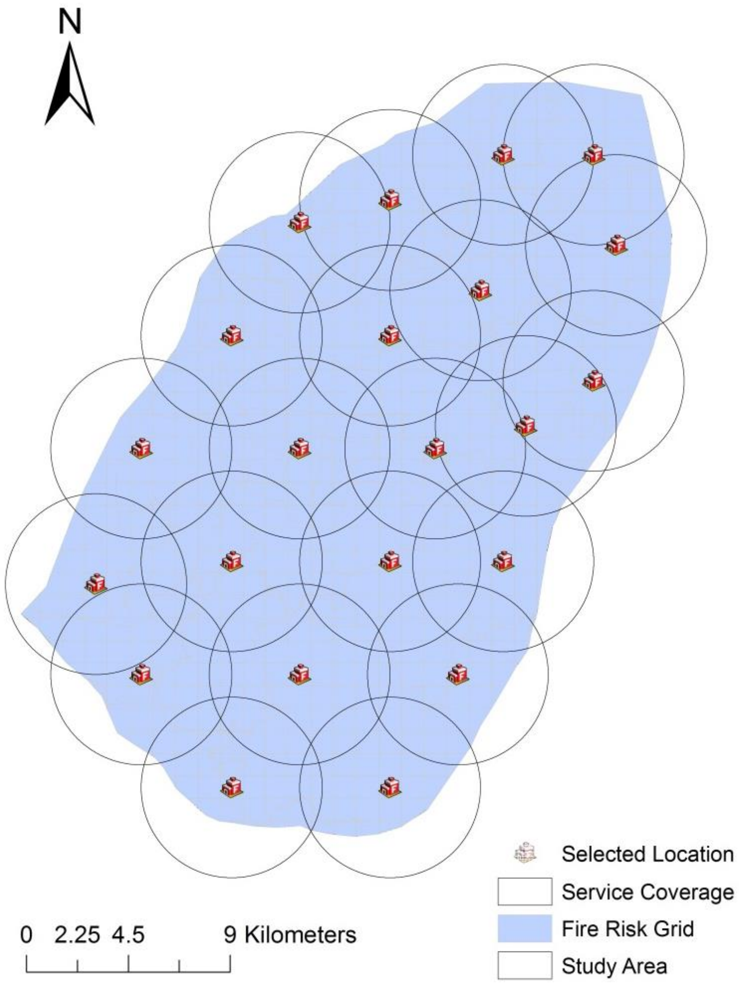
Integer requirements

Toregas, C., Swain, R., ReVelle, C., & Bergman, L. (1971). The location of emergency service facilities. *Operations research*, *19*(6), 1363-1373.

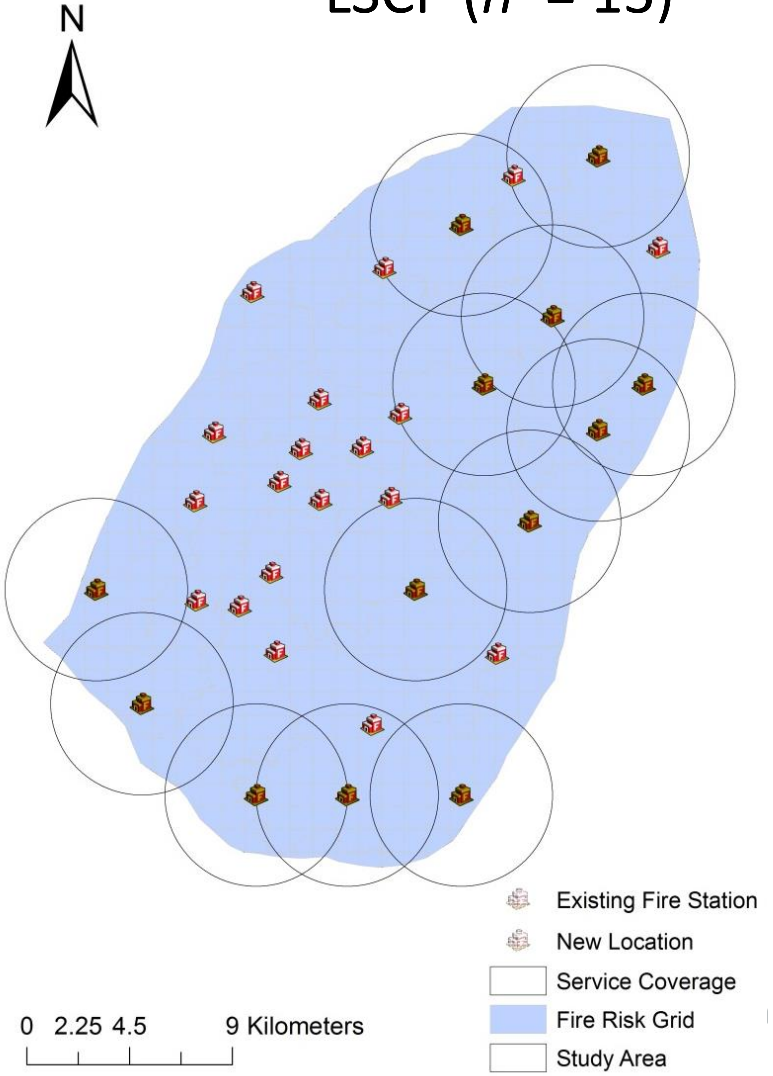
Example: optimizing fire station locations in Nanjing, China



LSCP (n = 22)



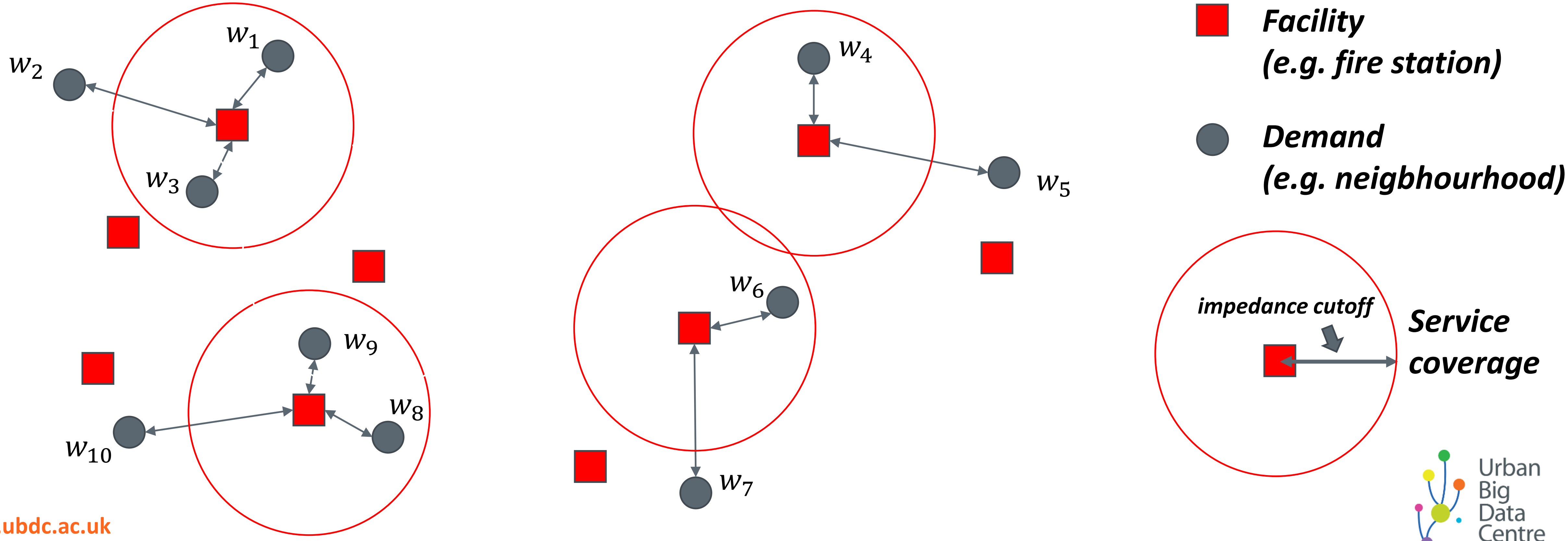
LSCP (n' = 13)



Yao, J., Zhang, X., & Murray, A. T. (2019). Location optimization of urban fire stations: Access and service coverage. *Computers, Environment and Urban Systems*, 73, 184-190.

Maximal Covering Location Problem (MCLP)

- Locate a pre-specified number of facilities such that coverage within a maximal service distance or time is maximized.



Maximal Covering Location Problem (MCLP)

Mathematical Representation

Notation

- i = index of demand areas
- j = index of potential facility locations
- $a_{ij} = \begin{cases} 1 \text{ if area } i \text{ is suitably servied by a potential facility at site } j \\ 0 \text{ otherwise} \end{cases}$.
- $N_i = \{j | a_{ij} = 1\}$
- w_j = amount of demand in area i
- p = number of facilities to be located

Decision Variables

- $X_j = \begin{cases} 1 \text{ if potential facility } j \text{ is located} \\ 0 \text{ otherwise} \end{cases}$
- $Y_i = \begin{cases} 1 \text{ if area } i \text{ is provided coverage} \\ 0 \text{ otherwise} \end{cases}$

Maximize $\sum_i w_i Y_i$

Subject to

(1) $\sum_{j \in N_i} X_j - Y_i \geq 0 \quad \forall i$

Account for demand area provided suitable coverage

(2) $\sum_j X_j = p$

Locate *p* facilities

(3) $X_j = \{0,1\} \quad \forall j$

$Y_i = \{0,1\} \quad \forall i$

Integer requirements

Church, R., & ReVelle, C. (1974). The maximal covering location problem. *Papers of the Regional Science Association*, 32(1), pp. 101-118). Springer-Verlag.

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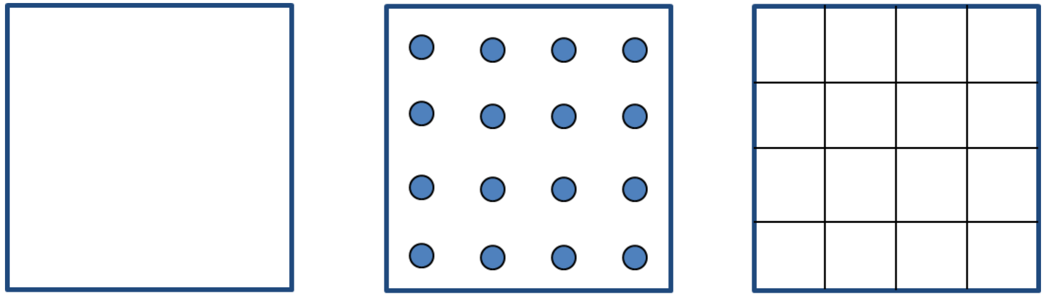
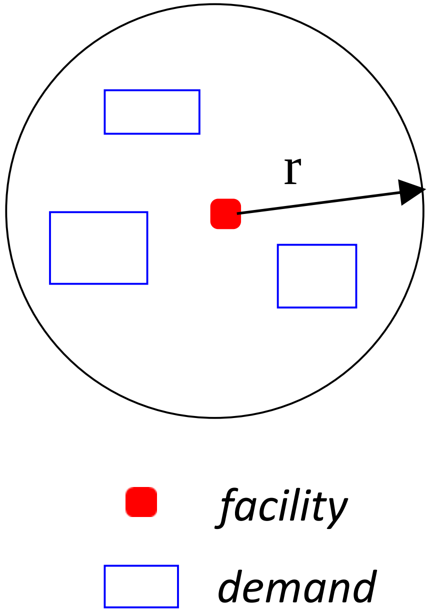
Role of GIS

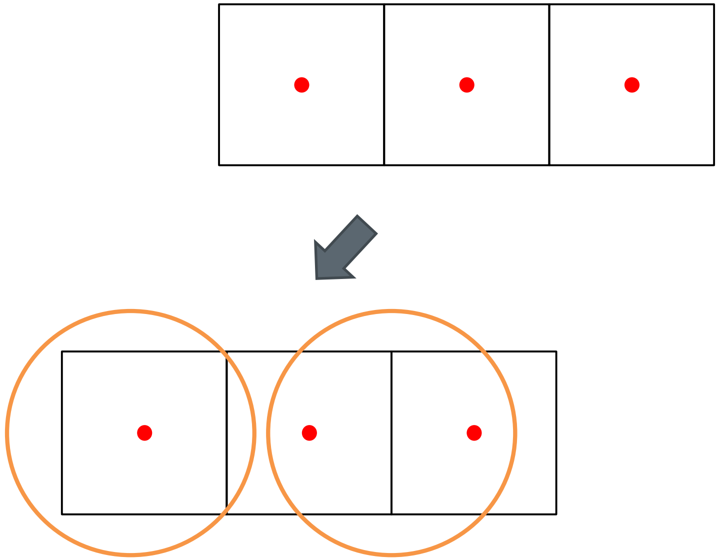
- Spatial representation
  - Region representation



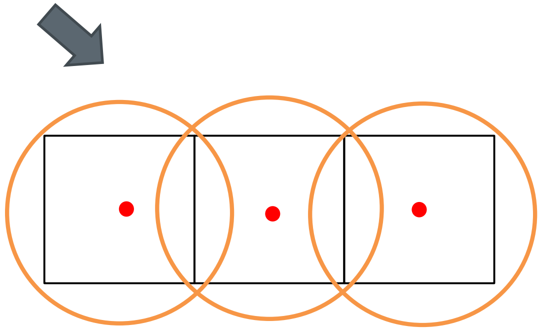
(a) Boundary (b) Point (c) Grid

- Assessing coverage
  - Distance
  - Travel time





Point Coverage

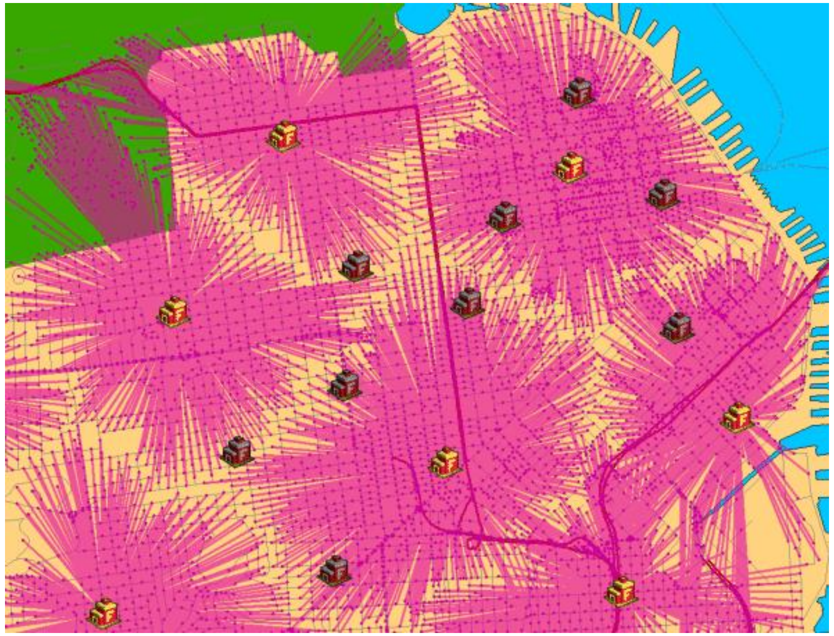


Polygon Coverage

3. Location-allocation Analysis in ArcGIS

Location-allocation Analysis in ArcGIS

- Location-allocation
  - Facilities: provide goods and services
  - Demand points: consume goods and services
- Goal
  - Helps you choose which facilities from a set of facilities to operate based on their potential interaction with demand points.
  - Simultaneously locates facilities and allocates demand points to the facilities



https://desktop.arcgis.com/en/arcmap/10.6/extensions/network-analyst/location-allocation.htm

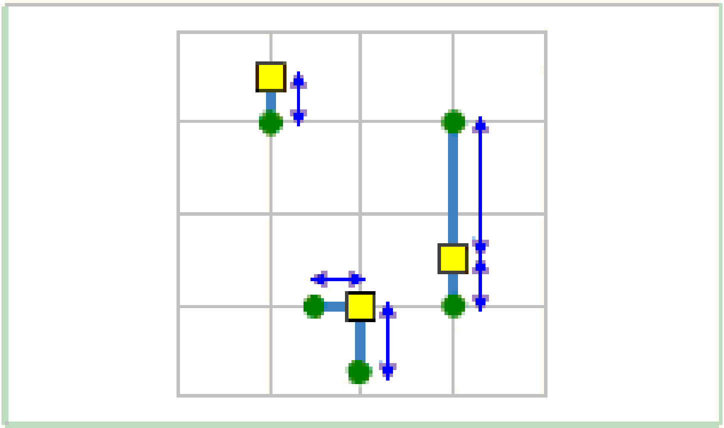
Location-allocation Problem Types

1. Minimize impedance
2. Maximize coverage
3. Maximize capacitated coverage
4. Minimize facilities
5. Maximize attendance
6. Maximize market share
7. Target market share

https://desktop.arcgis.com/en/arcmap/10.6/extensions/network-analyst/location-allocation.htm

Minimize Impedance

- Facilities are located such that the sum of all weighted costs between demand points and solution facilities is minimized.
- Traditionally used to locate warehouses, because it can reduce the overall transportation costs of delivering goods to outlets.
- Commonly used for locating public-sector facilities such as
  - libraries, regional airports, museums, department of motor vehicles offices, and health clinics.



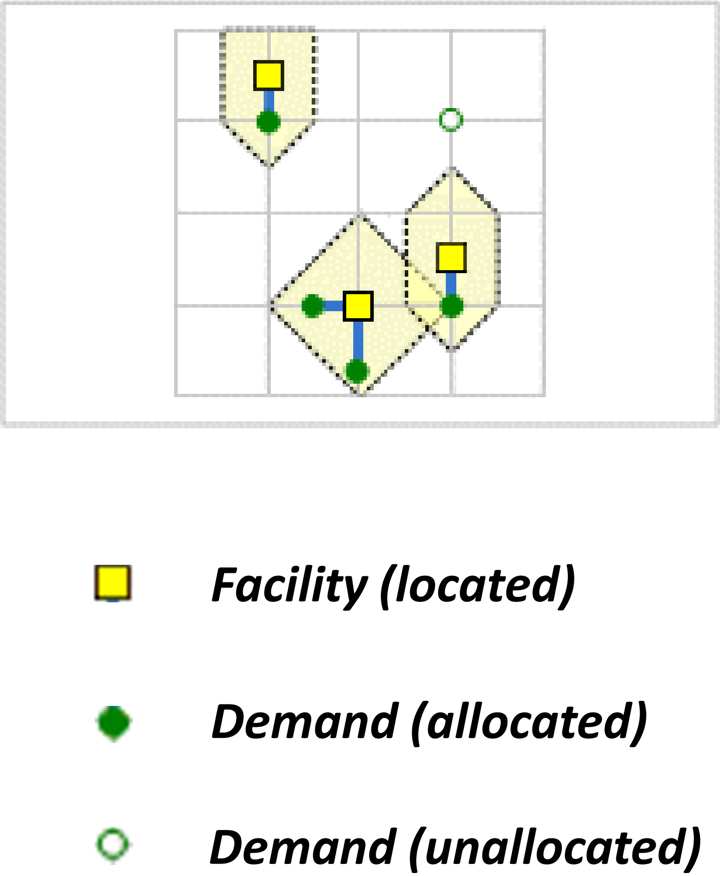
Facility (located)

Demand (allocated)

https://desktop.arcgis.com/en/arcmap/10.6/extensions/network-analyst/location-allocation.htm

Maximize Coverage

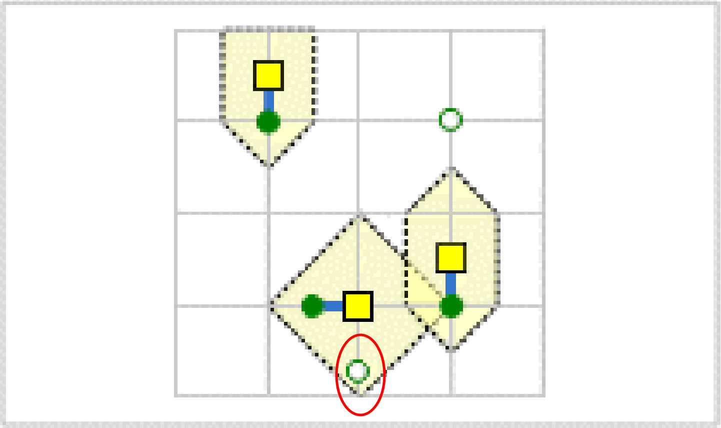
- Facilities are located such that as many demand points as possible are allocated to solution facilities within the impedance cutoff.
- Often used to locate fire stations, police stations, and emergency service centres, because emergency services are often required to arrive at all demand points within a specified response time.



https://desktop.arcgis.com/en/arcmap/10.6/extensions/network-analyst/location-allocation.htm

Maximize Capacitated Coverage

- Facilities are located such that as many demand points as possible are allocated to solution facilities within the impedance cutoff
  - The weighted demand allocated to a facility can't exceed the facility's capacity.
- Can be use for
  - creating territories that encompass a given number of people or businesses,
  - locating hospitals or other medical facilities with a limited number of beds or patients who can be treated,
  - locating warehouses whose inventory isn't assumed to be unlimited.



Facility (located)

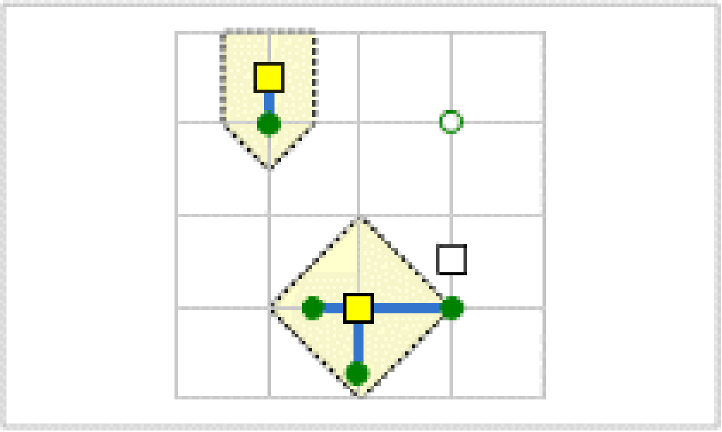
Demand (allocated)

Demand (unallocated)

https://desktop.arcgis.com/en/arcmap/10.6/extensions/network-analyst/location-allocation.htm

Minimize Facilities

- Facilities are located such that as many demand points as possible are allocated to solution facilities within the impedance cutoff
  - the number of facilities required to cover demand points is minimized.
- Use Minimize Facilities when the cost of building facilities is not a limiting factor.
  - e.g. to choose school bus stops when students are required to walk a certain distance before another school bus stop is provided closer to the student's residence.



Facility (located)

Facility (unlocated)

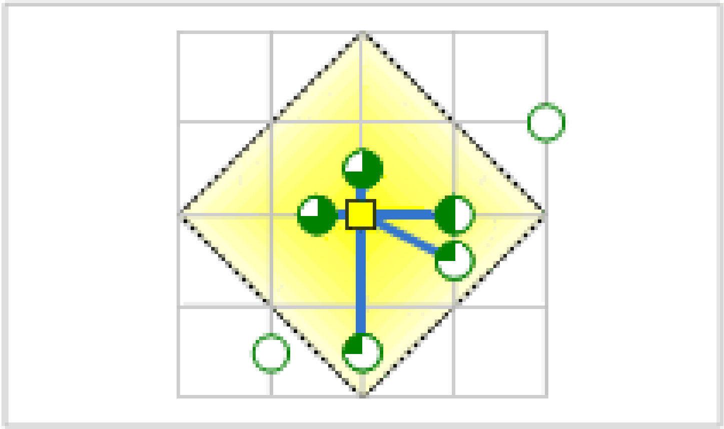
Demand (allocated)

Demand (unallocated)

https://desktop.arcgis.com/en/arcmap/10.6/extensions/network-analyst/location-allocation.htm

Maximize Attendance

- Facilities are chosen such that as much demand weight as possible is allocated to facilities while assuming the demand weight decreases in relation to the distance between the facility and the demand point.
- Assumes that the farther people have to travel to reach your facility, the less likely they are to use it.
- Public transit bus stops are often chosen with the help of Maximize Attendance.
- It may also be beneficial to
  - Specialty stores that have little or no competition
  - general retailers and restaurants that don't have the data on competitors.
  - Some businesses include coffee shops, fitness centres, dental and medical offices, bowling alleys, and electronics stores.



Facility (located)

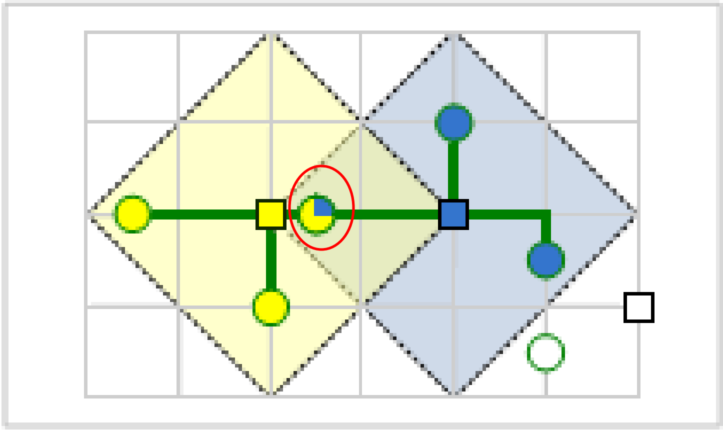
how much of total demand is captured by the facility

Demand (unallocated)

https://desktop.arcgis.com/en/arcmap/10.6/extensions/network-analyst/location-allocation.htm

Maximize Market Share

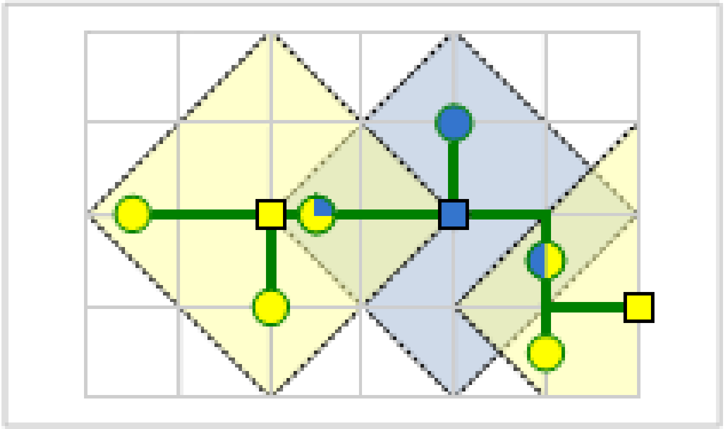
- A specific number of facilities are chosen such that the allocated demand is maximized in the presence of competitors.
- The goal is to capture as much of the total market share as possible with a given number of facilities, which you specify.
- The market share problem types use a Huff model, which is also known as a gravity model or spatial interaction.
- Large discount stores typically use Maximize Market Share to locate a finite set of new stores.



 *the percent of demand weight captured by the facility of the same colour*

Target Market Share

- Chooses the minimum number of facilities necessary to capture a specific percentage of the total market share in the presence of competitors.
  - budgets are not a concern
- Large discount stores typically use the Target Market Share problem type when they want to know
  - how much expansion would be required to reach a certain level of the market share or
  - see what strategy would be needed just to maintain their current market share given the introduction of new competing facilities.



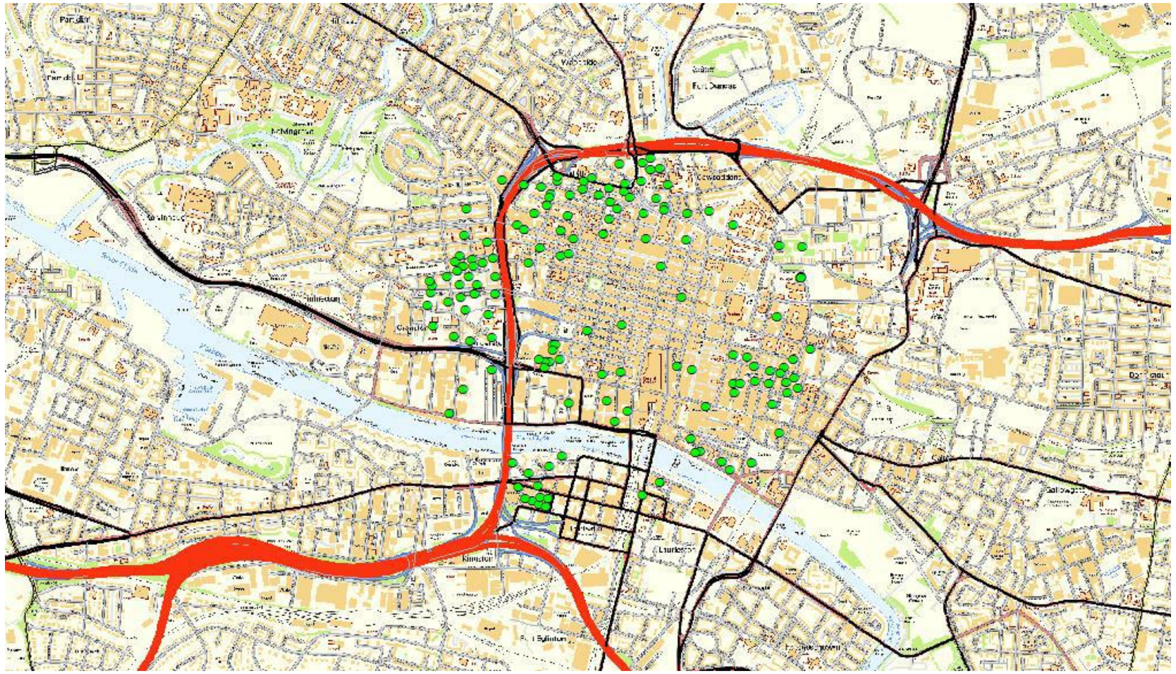
the percent of demand weight captured by the facility of the same colour

https://desktop.arcgis.com/en/arcmap/10.6/extensions/network-analyst/location-allocation.htm

4. Overview of the Tutorial

http://ubdc.ac.uk/education-and-events/events-and-courses/upcoming-events/gis-based-facility-location-analysis-for-the-public-and-private-sectors/

- Problem statement
  - to locate some recycling facilities (glass recycling bins for example) in Glasgow city centre
- Data
  - Road network
  - Centroids of output areas of Glasgow: facility & demand
  - Demand weight: the number of people living in each area



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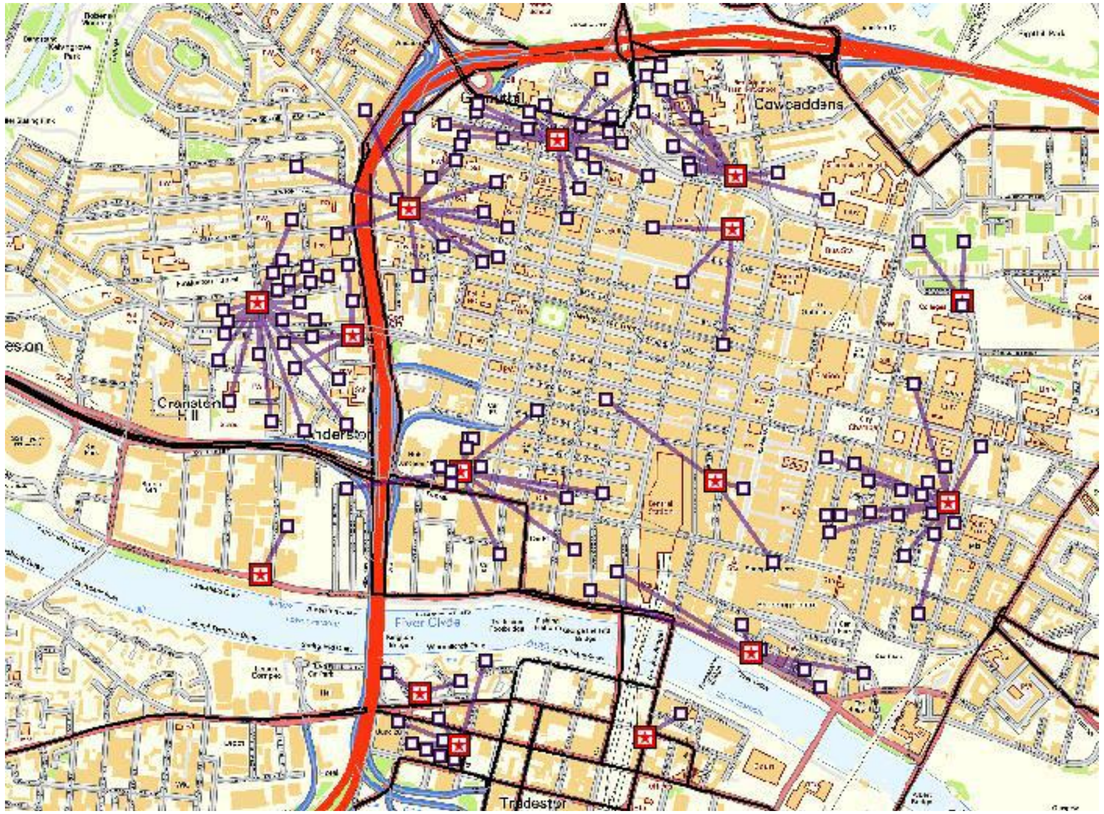
Example 1: Minimize Facilities

- Assume everyone should be within a 500 *m* distance of a recycling bin
- We want to know
  - what is the smallest number of bins we could use to do this, and
  - where should we place them



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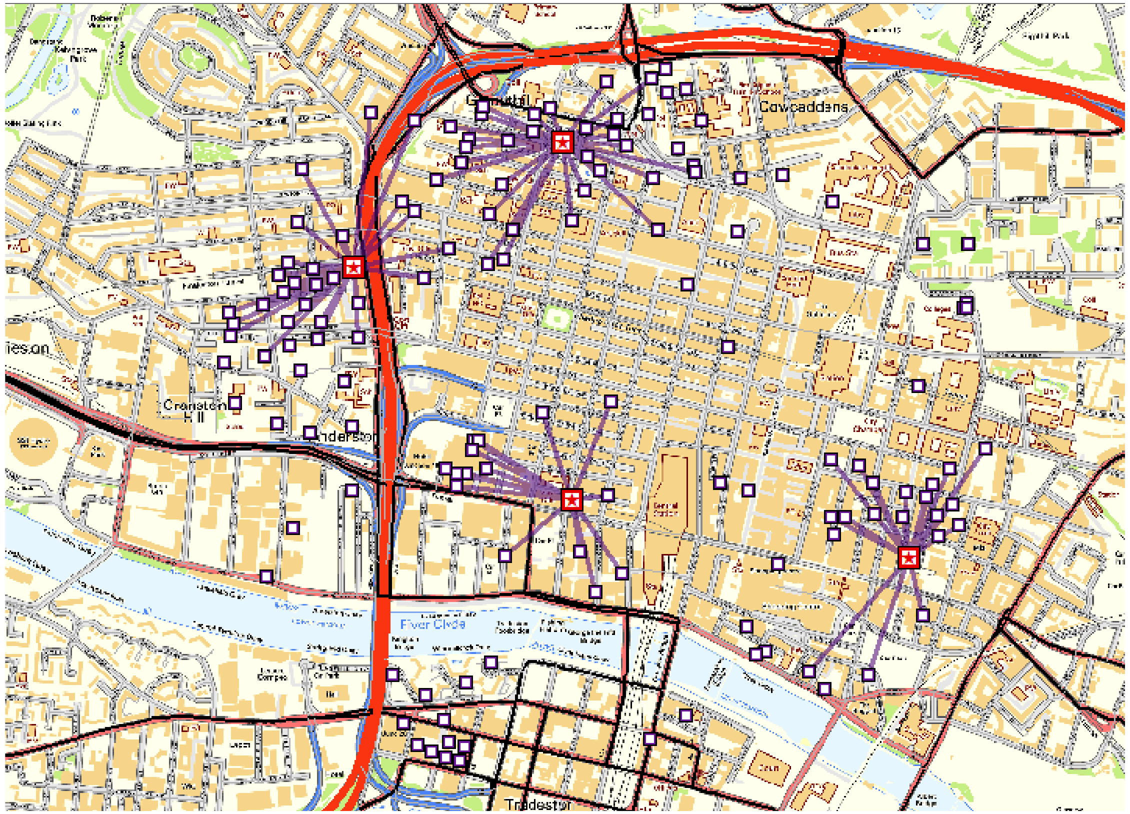
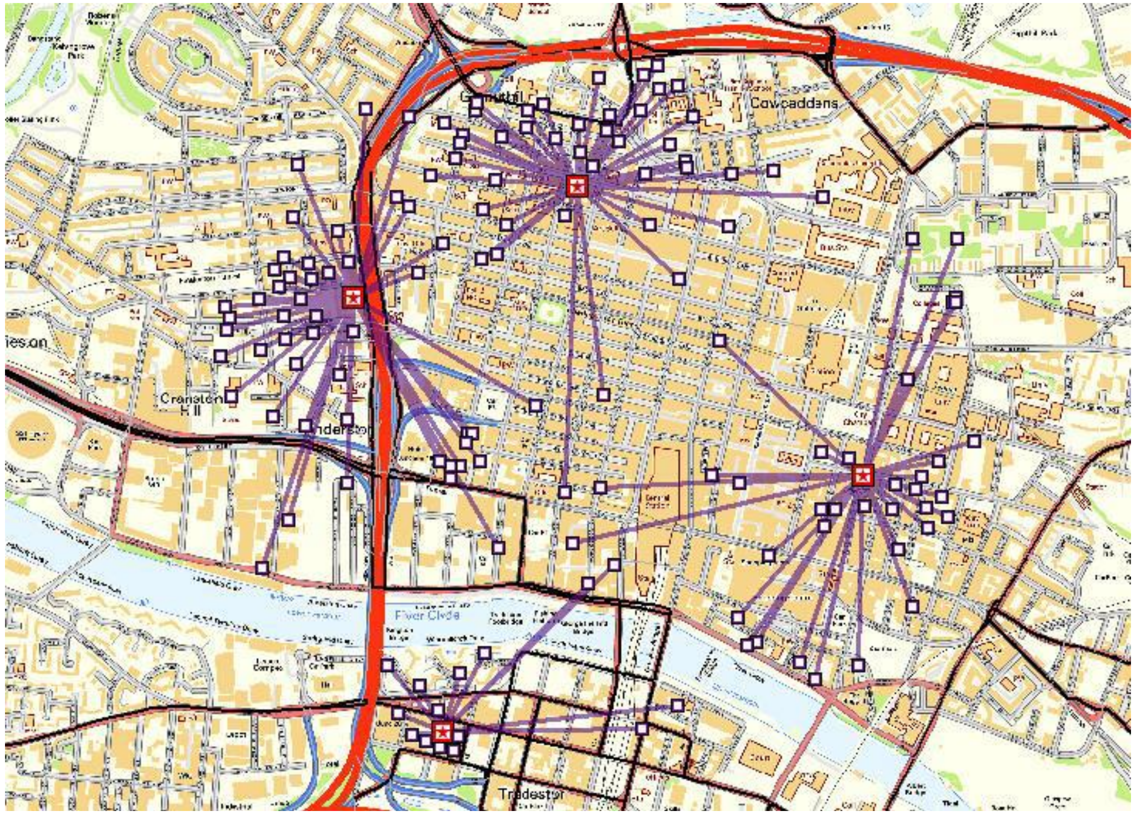
Example 2: Maximize Coverage

- Assume
  - everyone should be within a 500 *m* distance of a recycling bin
  - we have a budget to have four recycling facilities
- Where should we place them?



Example 3: Minimize Impedance

- To minimize the weighted distance from each demand node to each recycling facility
- We will locate four facilities
- No impedance cutoff



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The End

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