# Debris Removal During Disaster Response Phase:
# A Case for Turkey

# Debris

Definition:

*scattered fragments, typically of something wrecked or destroyed*

# Debris

- *Debris occurs because of*
  *-destruction of structures*

- *Debris quantity depends on*
  *-disaster's characteristics*
  *-disaster's magnitude*

- *Debris obstructs to transmit*
  *-emergency relief supplies to the disaster victims*

- *Inappropriate, inefficient and late removal of debris causes*
  *-delay in transportation and access to disaster victims*
  *-loss of lives!*

# Recent Disasters' Data

*1994,* <u>Northridge USA,</u> 10,000 tons of Construction & Demolition Materials

*1999,* <u>Gölcük Earthquake</u>, 112.735 buildings

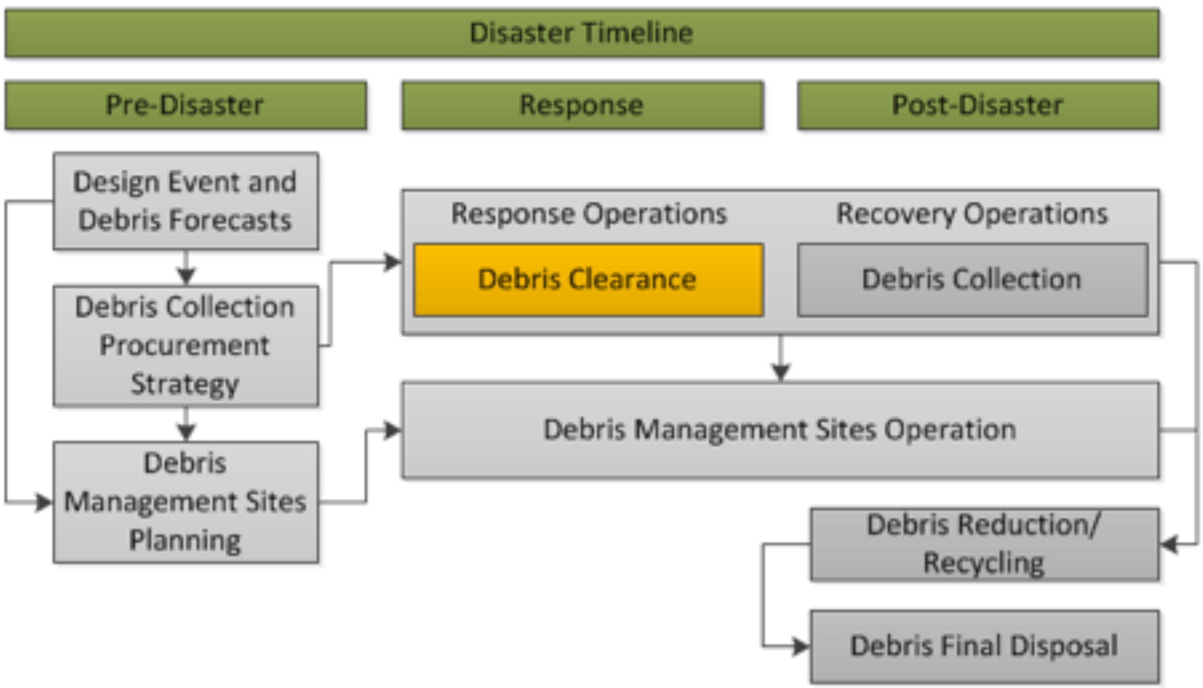
*2005,* <u>Hurricane Katrina</u>, 50.000.000 tons wood debris

*2011*, <u>Van Earthquake</u>, 2262 buildings

*2011,* <u>Fukushima Eartquake</u>, 1.000.000 tons C&D Materials

# Debris Removal

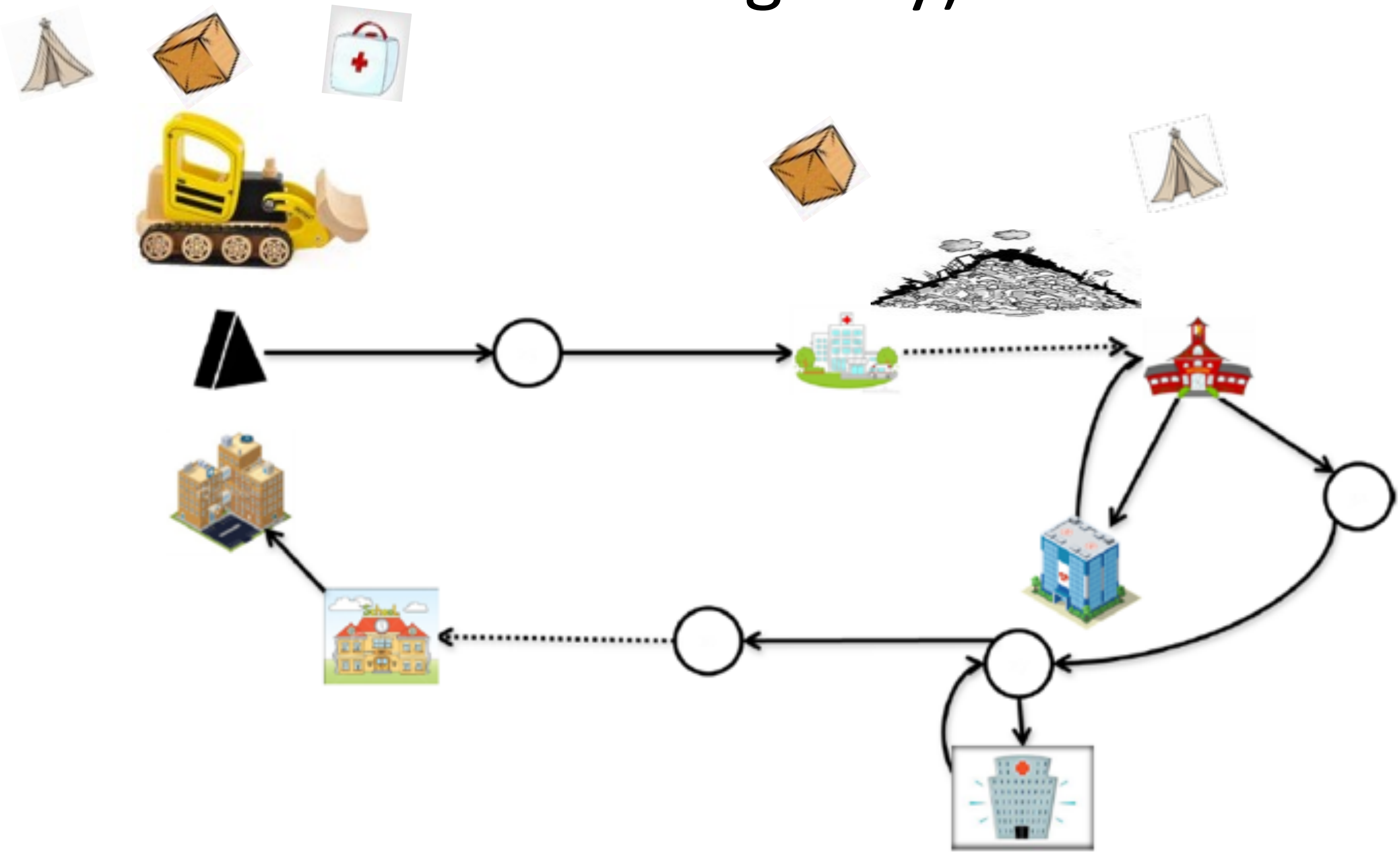
*Disaster timeline relating to debris operations [Çelik et al. 2013]*



# Problem Definition

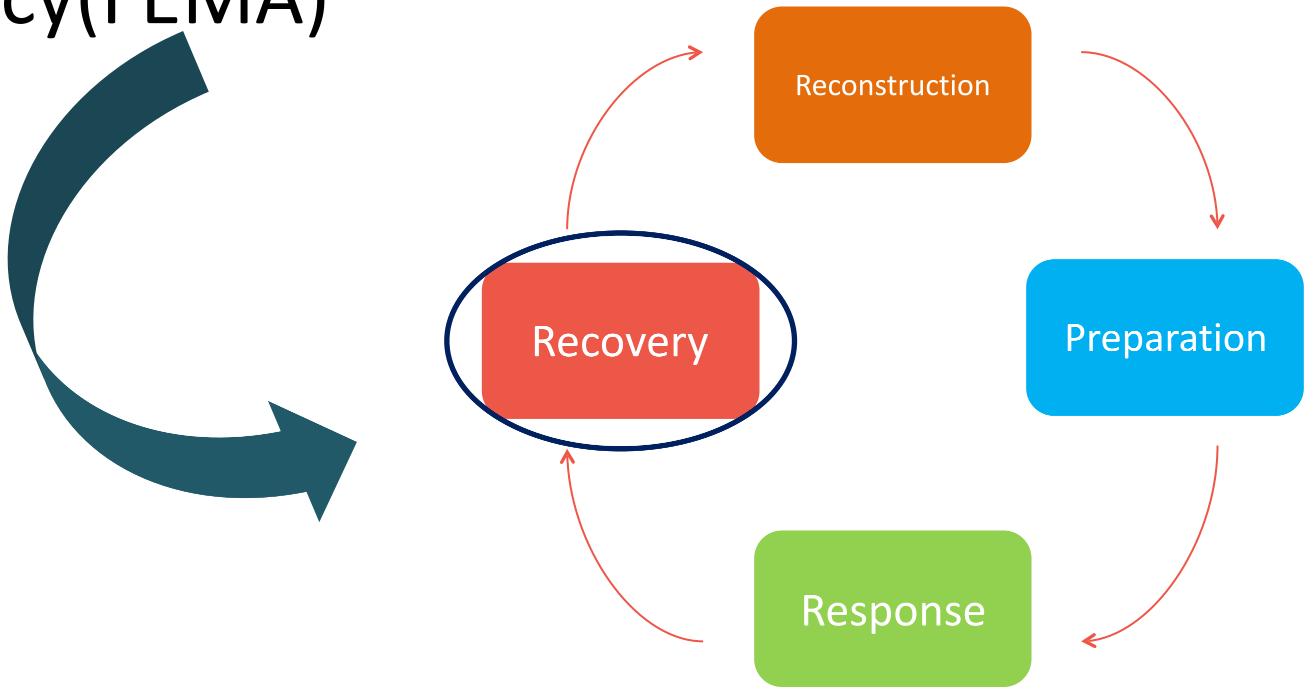
- «**Debris Removal Problem in the Response Phase**»:
  - In the phase of response
    - transmit emergency relief materials to the disaster affected regions as soon as possible
    - by considering some priorities among them
      - Districts with dense population
      - Districts containing hospital, shelter areas, schools
    - where some of the roads may proper to traversing, whereas some of them are blocked by the debris
      - Travel on a path which may include blocked roads as well
      - Unblock these roads by debris removing operations!

# RESCUE( **Re**lief **S**upply **C**arrier **U**nder **E**mergency)



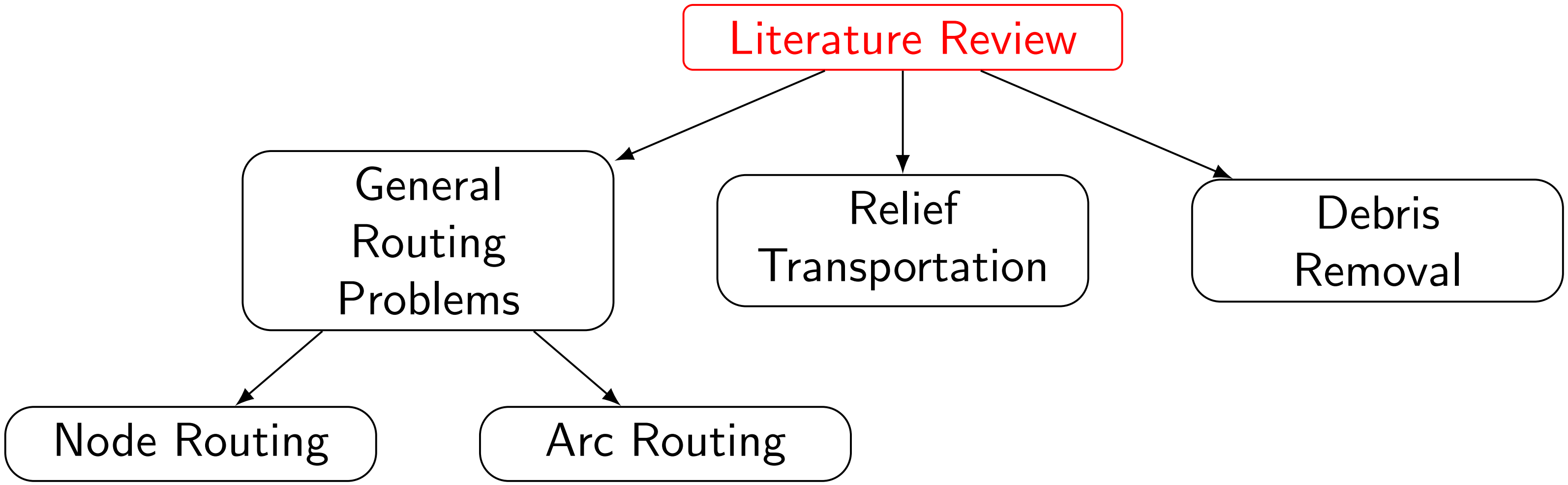
# Debris Removal Problem in the Literature

- USA, Federal Emergency Management Agency(FEMA)

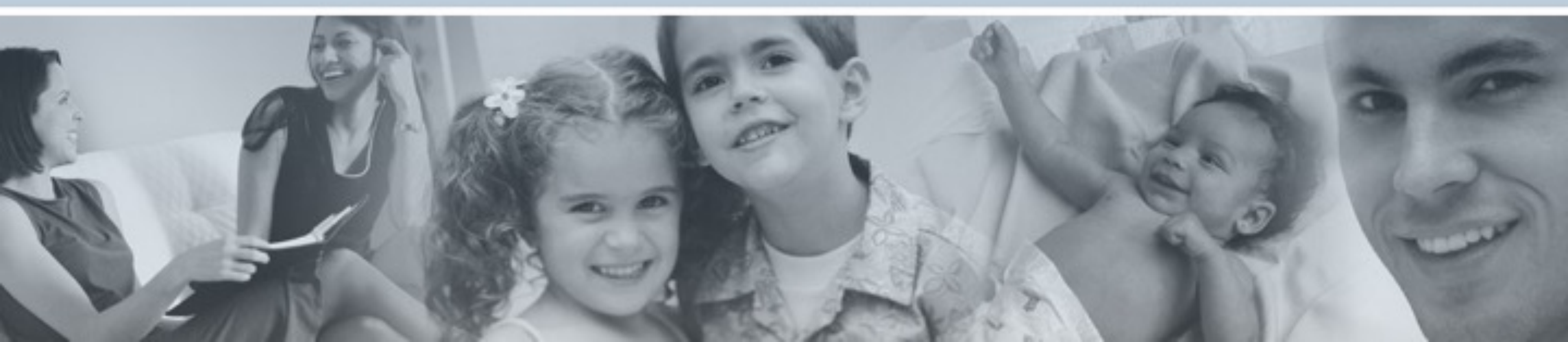


# Problem Definition

- **«Debris Removal Problem in the Response Phase»:**
  - In the phase of response
    - transmit emergency relief materials to the disaster affected regions as soon as possible
    - by considering some priorities among them
      - Districts with dense population
      - Districts containing hospital, shelter areas, schools
    - where some of the roads may proper to traversing, whereas some of them are blocked by the debris
      - Travel on a path which may include blocked roads as well
      - Unblock these roads by debris removing operations!


Literature Review
General Routing Problems
Relief Transportation
Debris Removal
Node Routing
Arc Routing

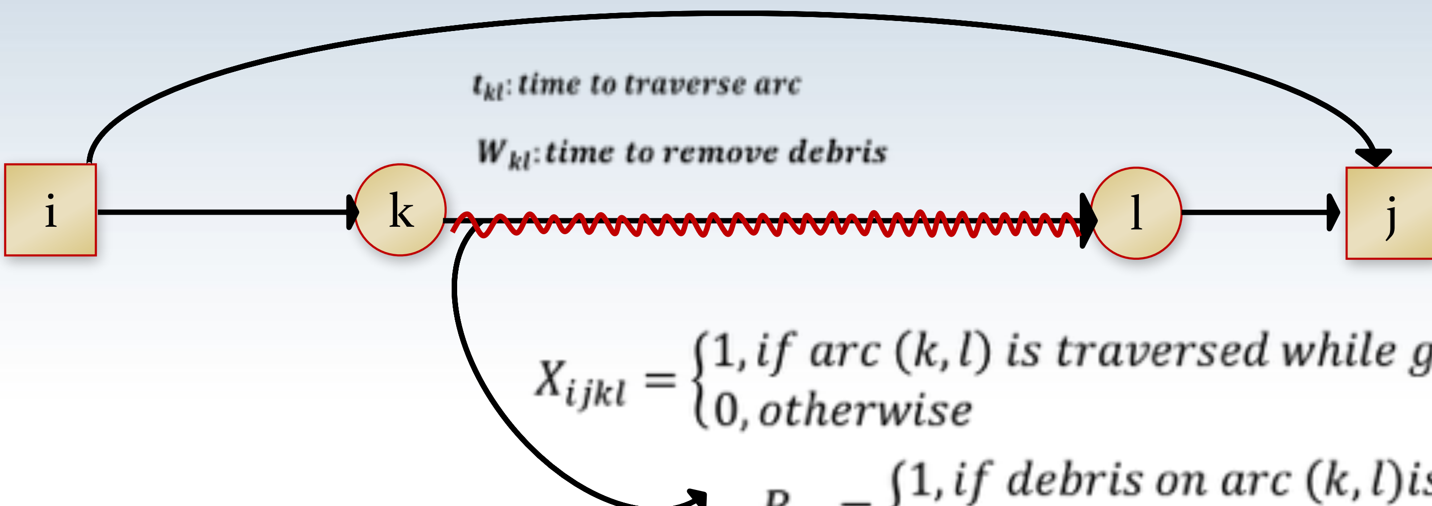
# Mathematical Model



# Suggested Solution

- Conceptually
  - Find a **visiting order** between critical nodes
    - Find the **least cost path** between two consecutive critical nodes

$$Y_{ij} = \begin{cases} 1, if\ i\ and\ j\ are\ consecutive\ critical\ nodes \\ 0, otherwise \end{cases}$$




$$X_{ijkl} = \begin{cases} 1, if\ arc\ (k,l)\ is\ traversed\ while\ going\ from\ i\ to\ j \\ 0, otherwise \end{cases}$$

$$B_{kl} = \begin{cases} 1, if\ debris\ on\ arc\ (k,l) is\ removed \\ 0, otherwise \end{cases}$$

# Variables

$$Y_{ij} = \begin{cases} 1 & \text{if critical node j is visited right after i} \\ 0 & \text{otherwise} \end{cases}$$

$$X_{ijkl} = \begin{cases} 1 & \text{if arc (k,l) is used in the path between critical nodes i \& j} \\ 0 & \text{otherwise} \end{cases}$$

$$B_{kl} = \begin{cases} 1 & \text{if blocked arc (k,l) is cleaned} \\ 0 & \text{otherwise} \end{cases}$$

$C_{ij}$ = Travel time of the path between i & j

$p_i$ = Cleaning efforts needed till node i

$$Min \quad TT + \sum_{k,l \in r : k<l} B_{kl} W_{kl}$$

$s.t.$

Minimize total effort

$$\sum_{j \in DL \cup SL : i \neq j} Y_{ji} = 1 \qquad \forall i \in DL$$

$$\sum_{j \in DL \cup SL : i \neq j} Y_{ij} = 1 \qquad \forall i \in DL$$

Construct a visiting sequence between DL = critical nodes

$$\sum_{j \in DL} Y_{ij} = 1 \qquad \forall i \in SL$$

$$\sum_{l \in N} X_{ijkl} - \sum_{l \in N} X_{ijlk} = Y_{ij} \qquad \forall i, j \in DL \cup SL, k = i$$

$$\sum_{l \in N} X_{ijkl} - \sum_{l \in N} X_{ijlk} = -Y_{ij} \qquad \forall i, j \in DL \cup SL, k = j$$

Construct a path for the visiting sequence

$$\sum_{l \in N} X_{ijkl} - \sum_{l \in N} X_{ijlk} = 0 \qquad \forall i, j \in DL \cup SL, k \neq i \neq j$$

$$\sum_{i,j \in DL \cup SL} X_{ijkl} + \sum_{i,j \in DL \cup SL} X_{ijlk} \leq (B_{kl} + I_{kl}) * |\mathrm{DL}| * |\mathrm{DL}| \quad \forall k,l \in N, k < l$$

$$\sum_{k,l \in N} X_{ijkl} \leq Y_{ij} * |\mathrm{N}| * |\mathrm{N}| \quad \forall i,j \in DL \cup SL$$

$$TT \geq p_i \quad \forall i \in DL$$

$$p_i \geq p_j + C_{ij} - M(1 - Y_{ij}) \quad \forall i \in DL \cup SL, j \in DL$$

$$C_{ij} = \sum_{k,l \in N} t_{kl} X_{ijlk} \quad \forall i,j \in DL \cup SL$$

Calculate the effort for cleaning the blocked arcs

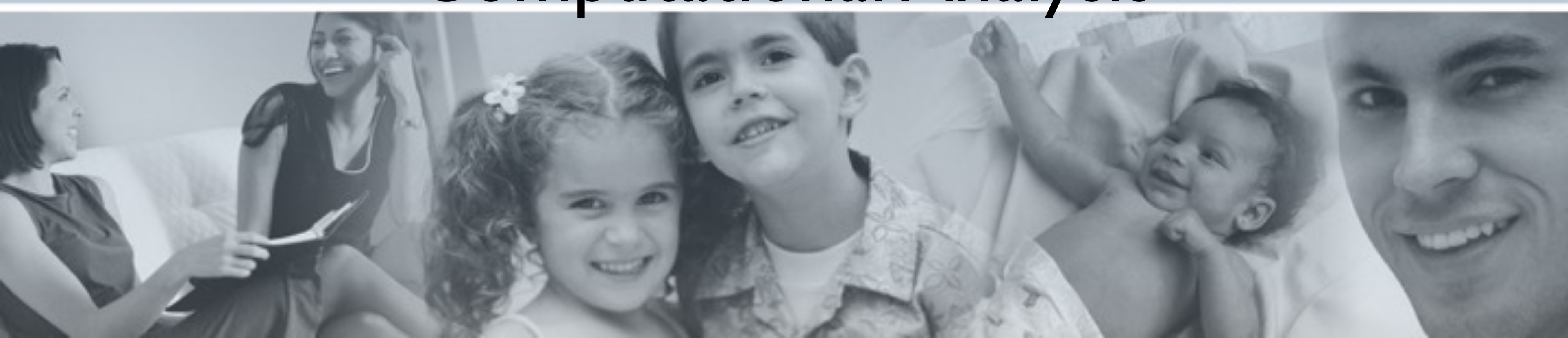
$$Y_{ij} \in \{0,1\}, C_{ij} \geq 0 \quad \forall i,j \in DL \cup SL$$

$$X_{ijkl} \in \{0,1\} \quad \forall i,j \in DL \cup SL, k,l \in N$$

$$P_i \geq 0 \quad \forall i \in DL \cup SL$$

$$B_{kl} \in \{0,1\} \quad \forall k,l \in N$$

# Computational Analysis



# Data Generation

- Kartal & Bakırkoy
    - Road infrastructure
    - Population
- Debris amount
    - Severity of Earthquake

| Severity of Earthquake | Blocked Arc Ratio |
|---|---|
| SOE=1 | 0%-20% |
| SOE=2 | 20%-50% |
| SOE=3 | 50%-80% |
| SOE=4 | 80%-100% |

$I_{kl} = 0$, for blocked arcs

- Randomly assigned
- Higher number of blocked arcs for more severe earthquakes

$W_{kl} = SOE * t_{kl} + U[0, \text{argmax}_{i,j} t_{ij}]$

$W'_{kl} = SOE * t_{kl}$

- Higher values for more severe earthquakes

# Data and Computational Results

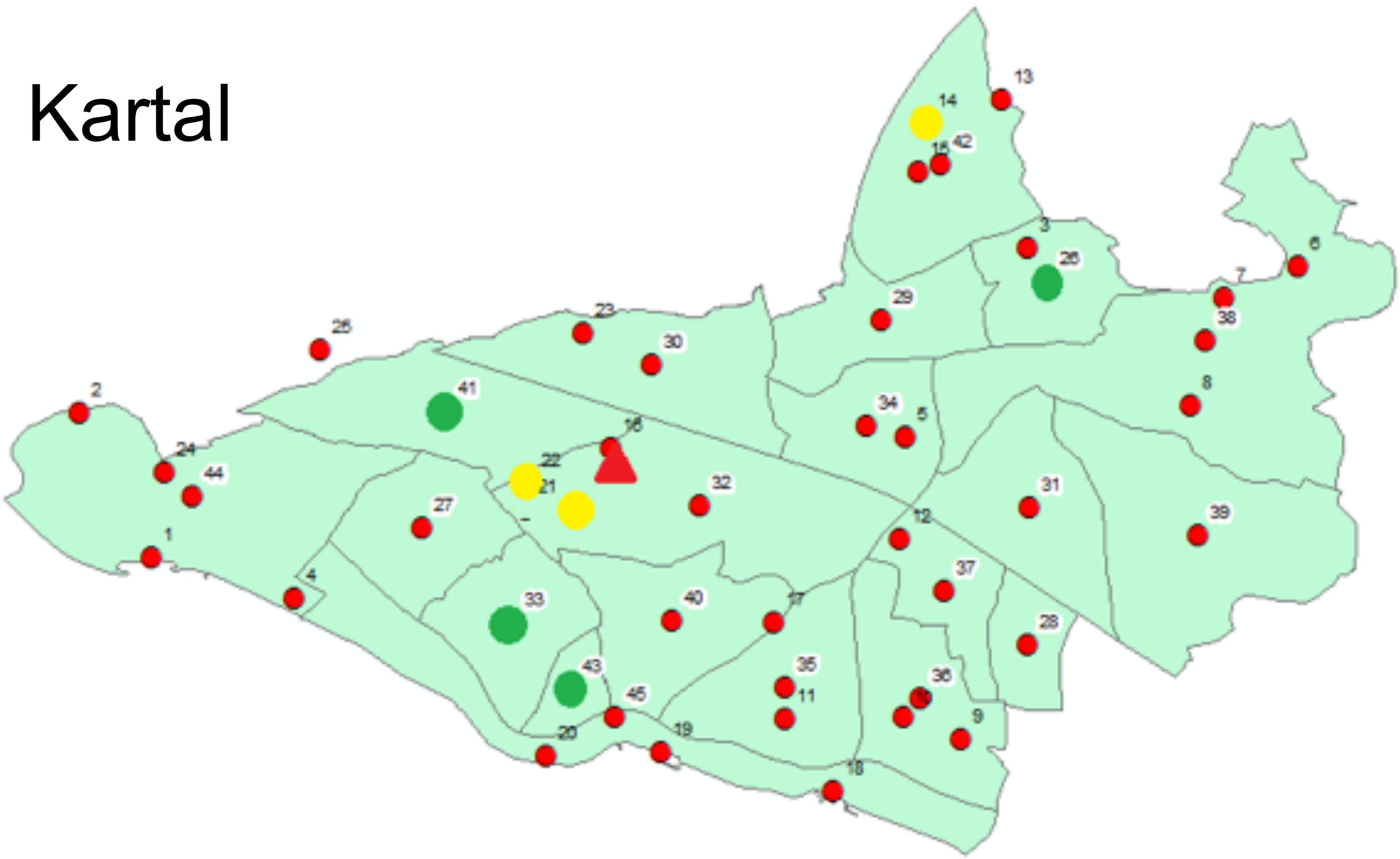
Kartal 45 nodes

| *Kartal* Instances | SOE | BAR | #of blocked arcs |
|---|---|---|---|
| K-1...K-5 K-1'...K-5' | 1 | 0.125 | 124 |
| K-6...K-10 K-6'...K-10' | 2 | 0.445 | 441 |
| K-11...K-15 K-11'...K-15' | 3 | 0.58 | 574 |
| K-16...K-20 K-16'...K-20' | 4 | 0.819 | 806 |

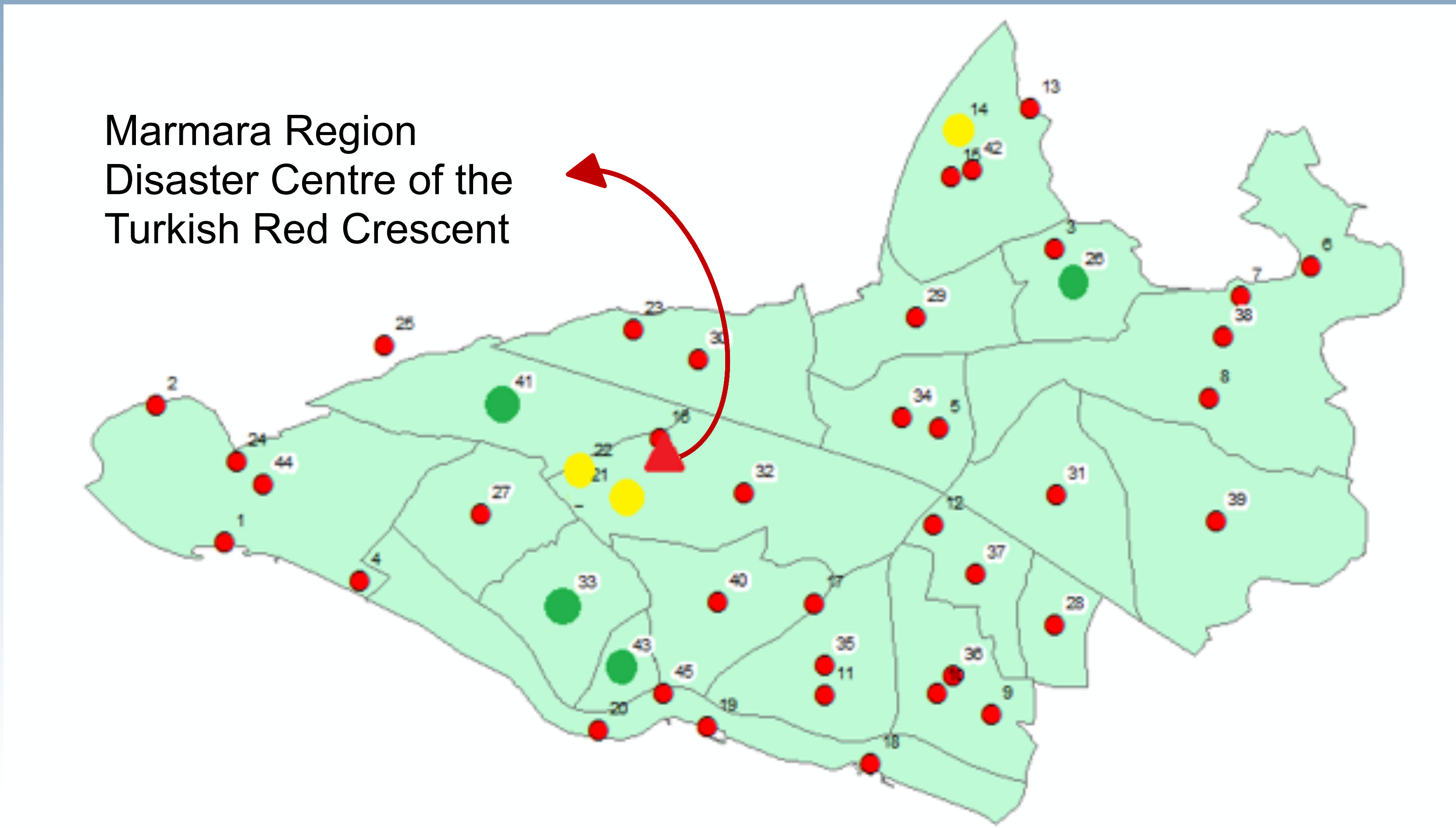
Bakırköy 74 nodes

| *Bakırköy* Instances | SOE | BAR | #of blocked arcs |
|---|---|---|---|
| B-1...B-5 B-1'...B-5' | 1 | 0.19 | 500 |
| B-6...B-10 B-6'...B-10' | 2 | 0.23 | 613 |
| B-11...B-15 B-11'...B-15' | 3 | 0.54 | 1423 |
| B-16...B-20 B-16'...B-20' | 4 | 0.82 | 2160 |

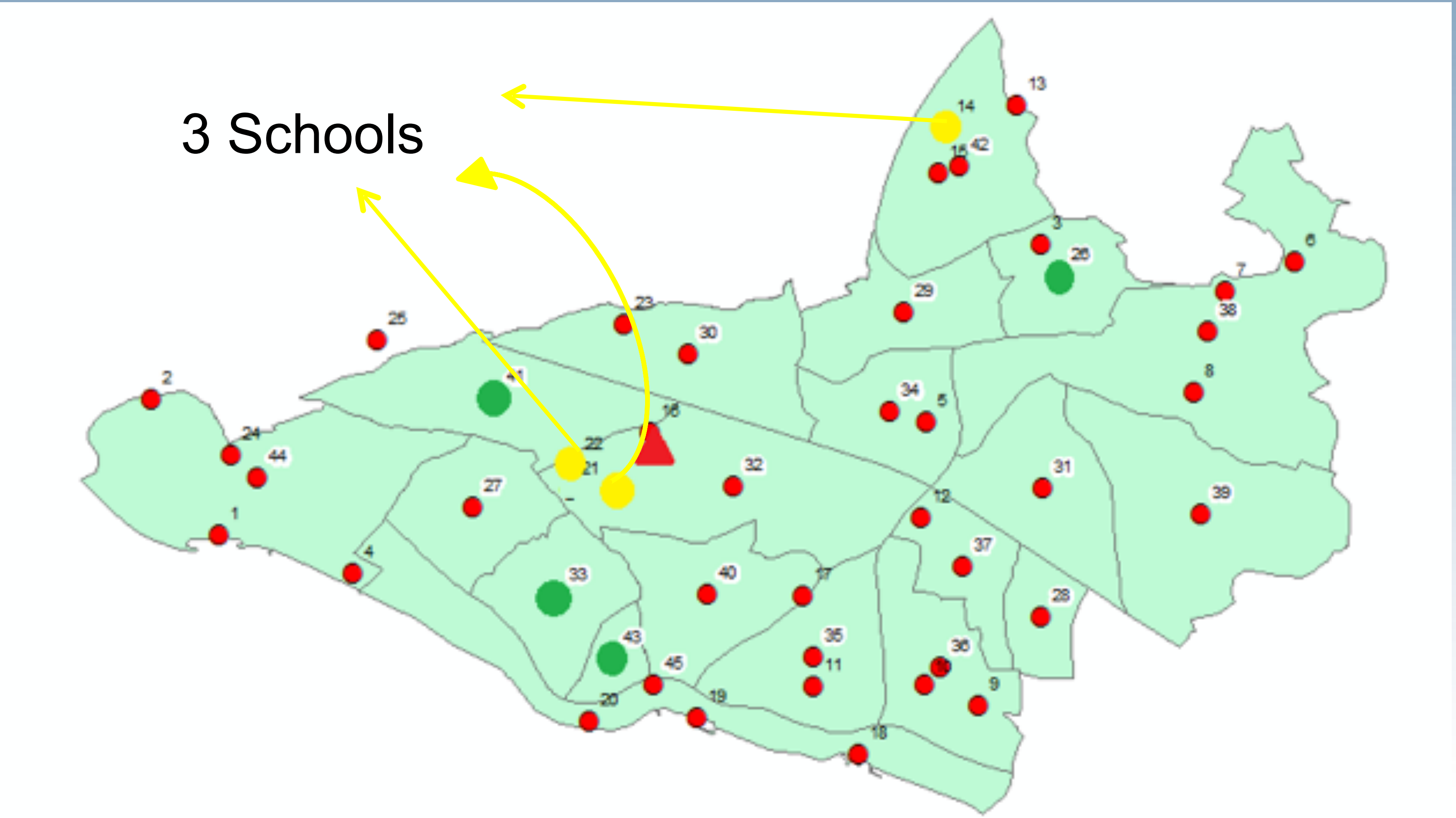
# Data and Computational Results



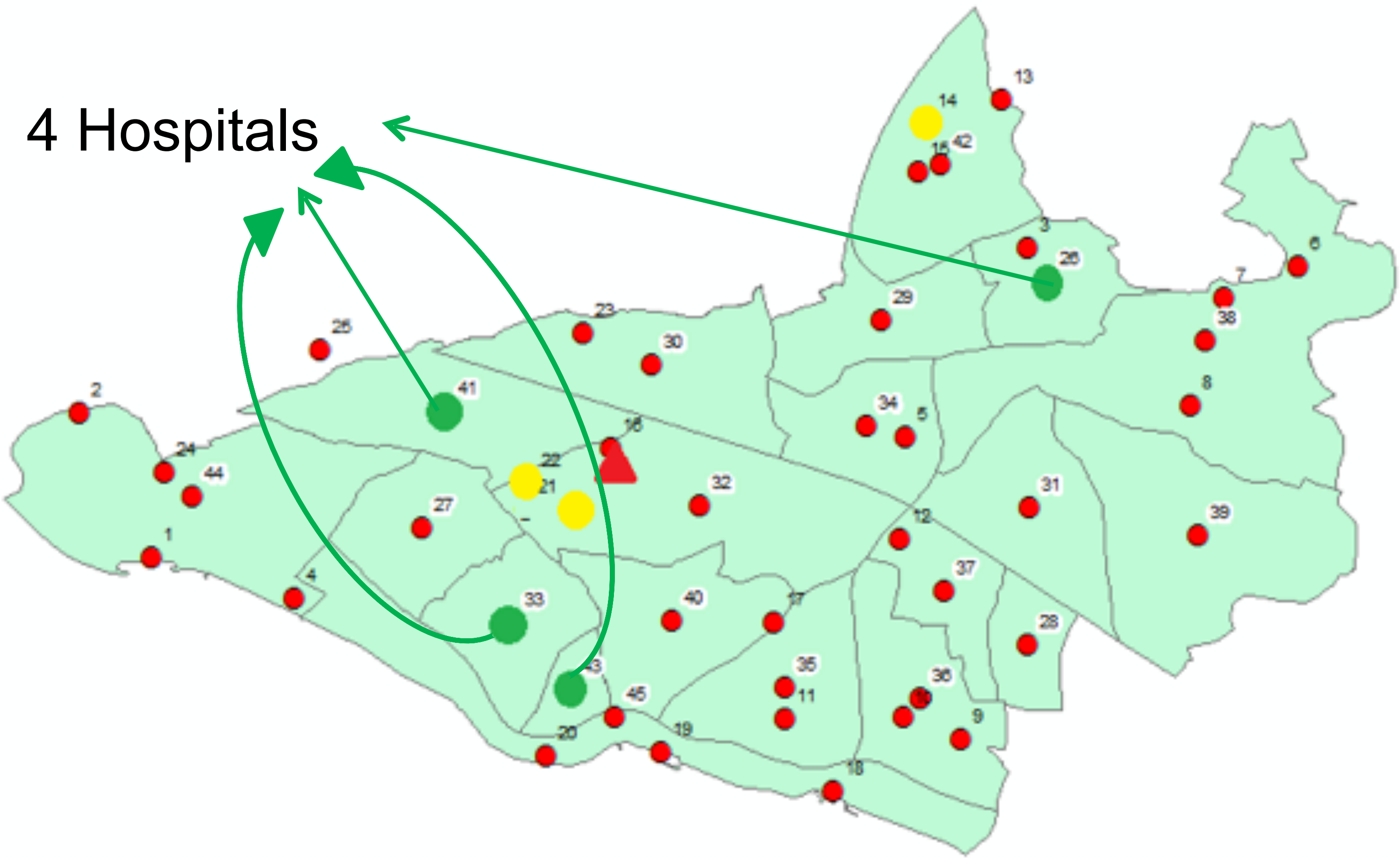
# Data and Computational Results



# Data and Computational Results

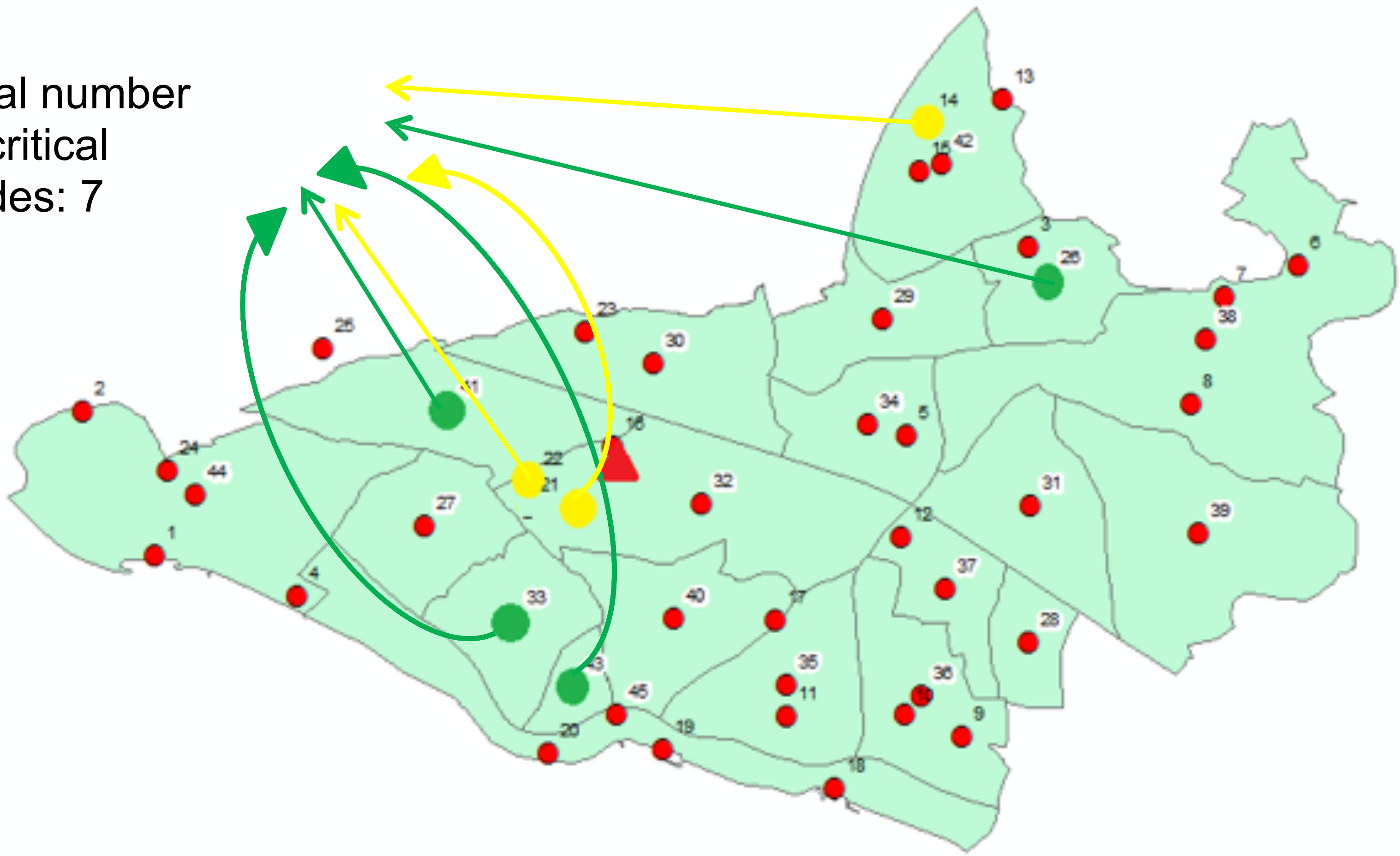


# Data and Computational Results



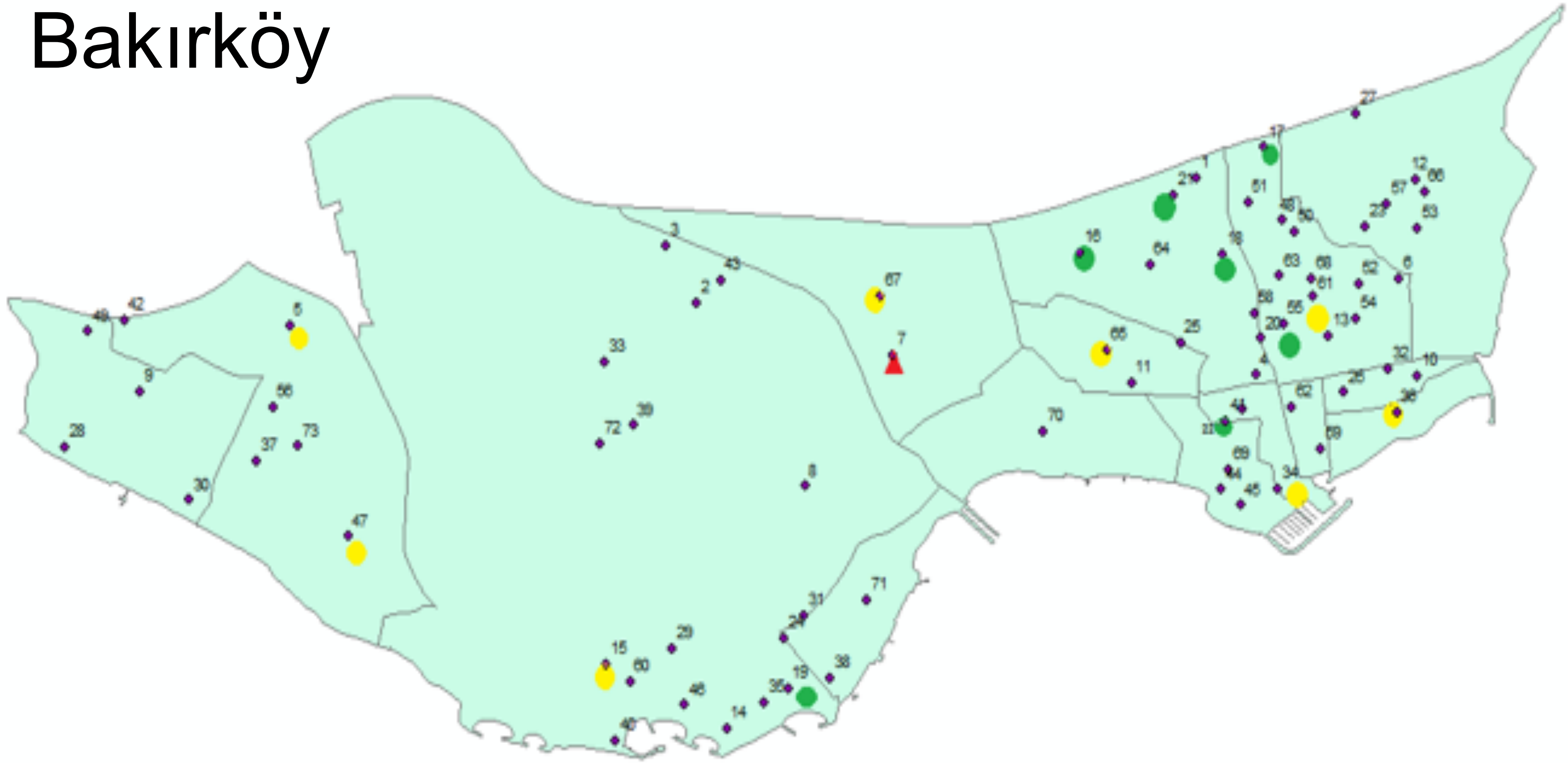
# Data and Computational Results

Total number of critical nodes: 7



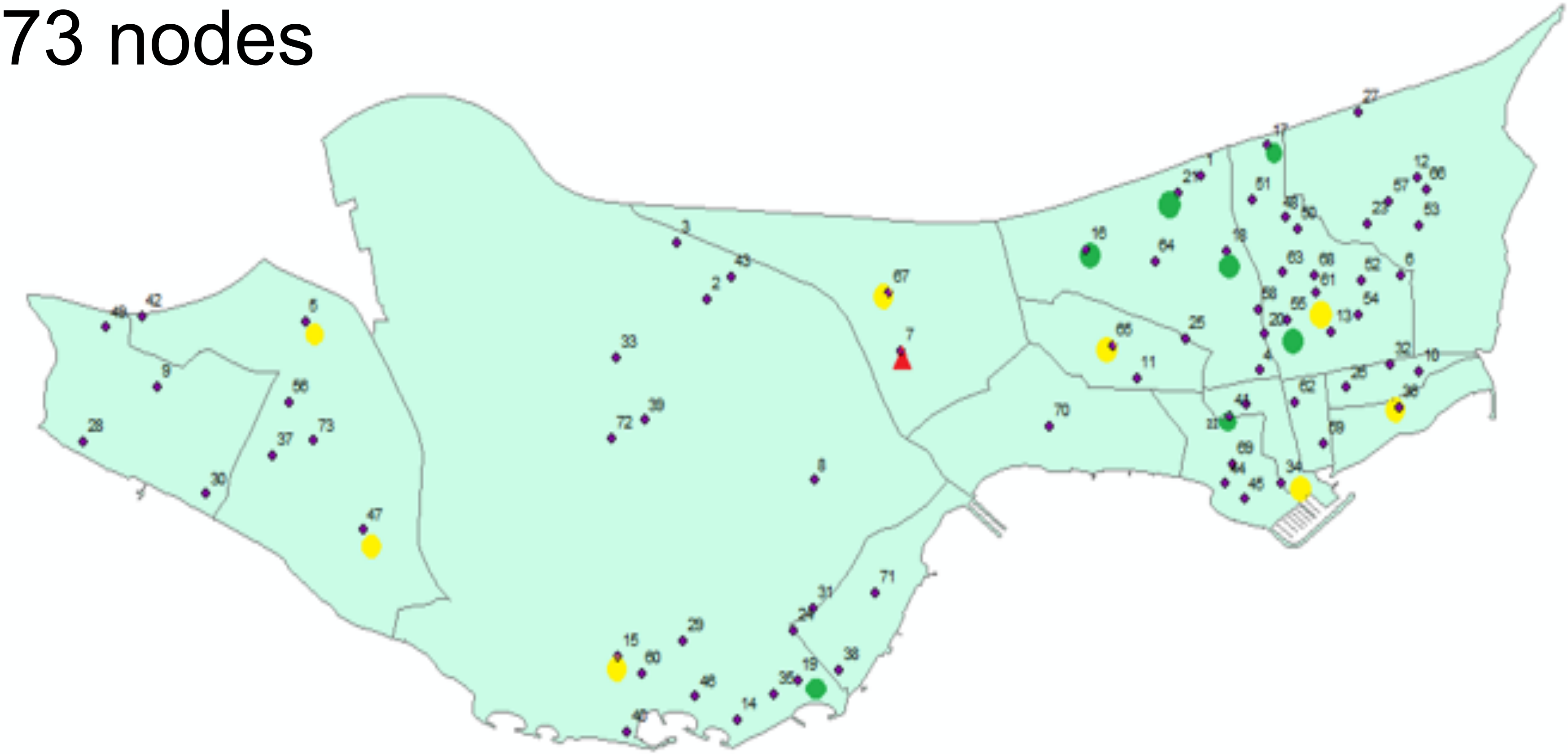
# Data and Computational Results

## Bakırköy

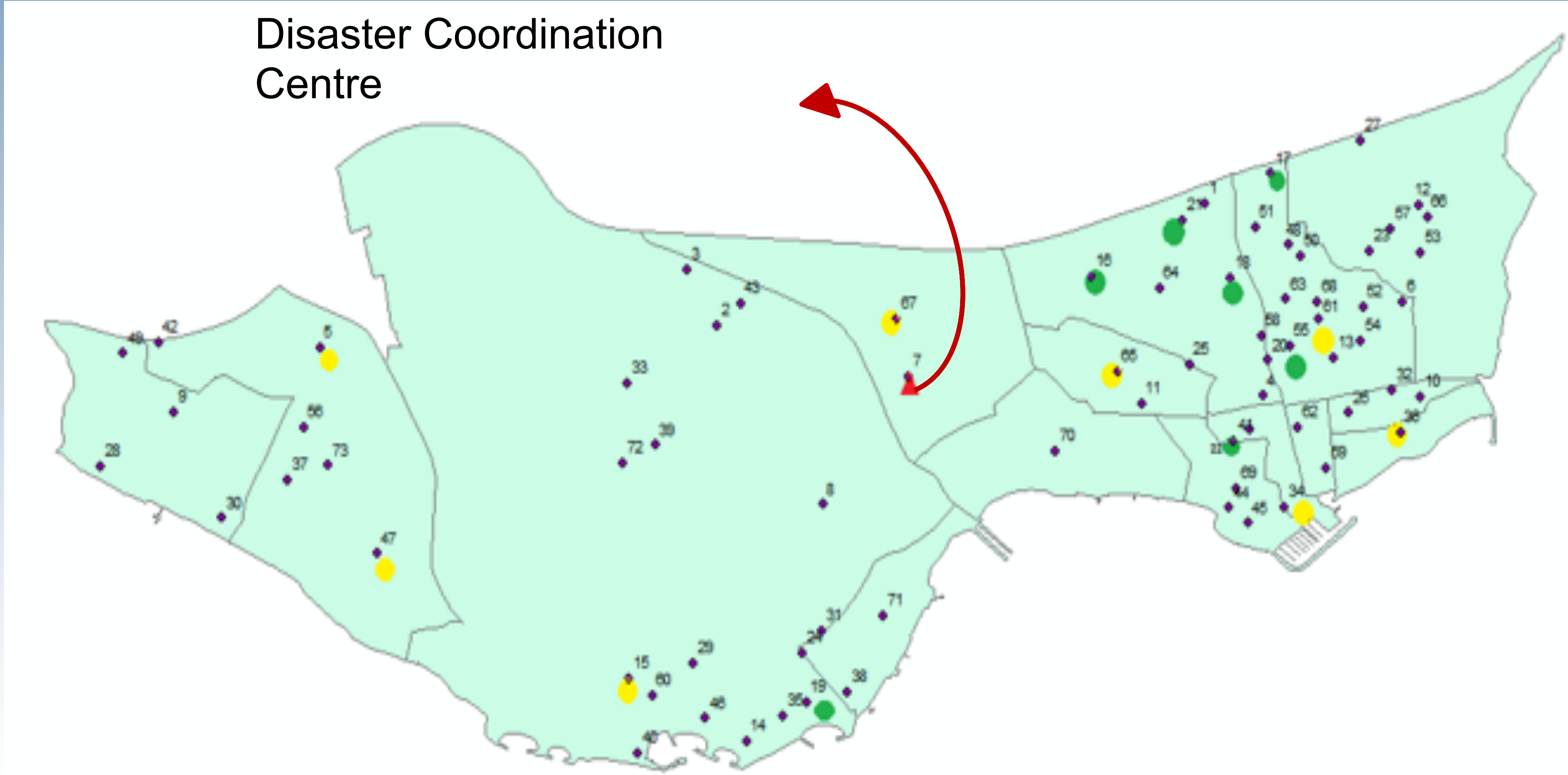


# Data and Computational Results

73 nodes

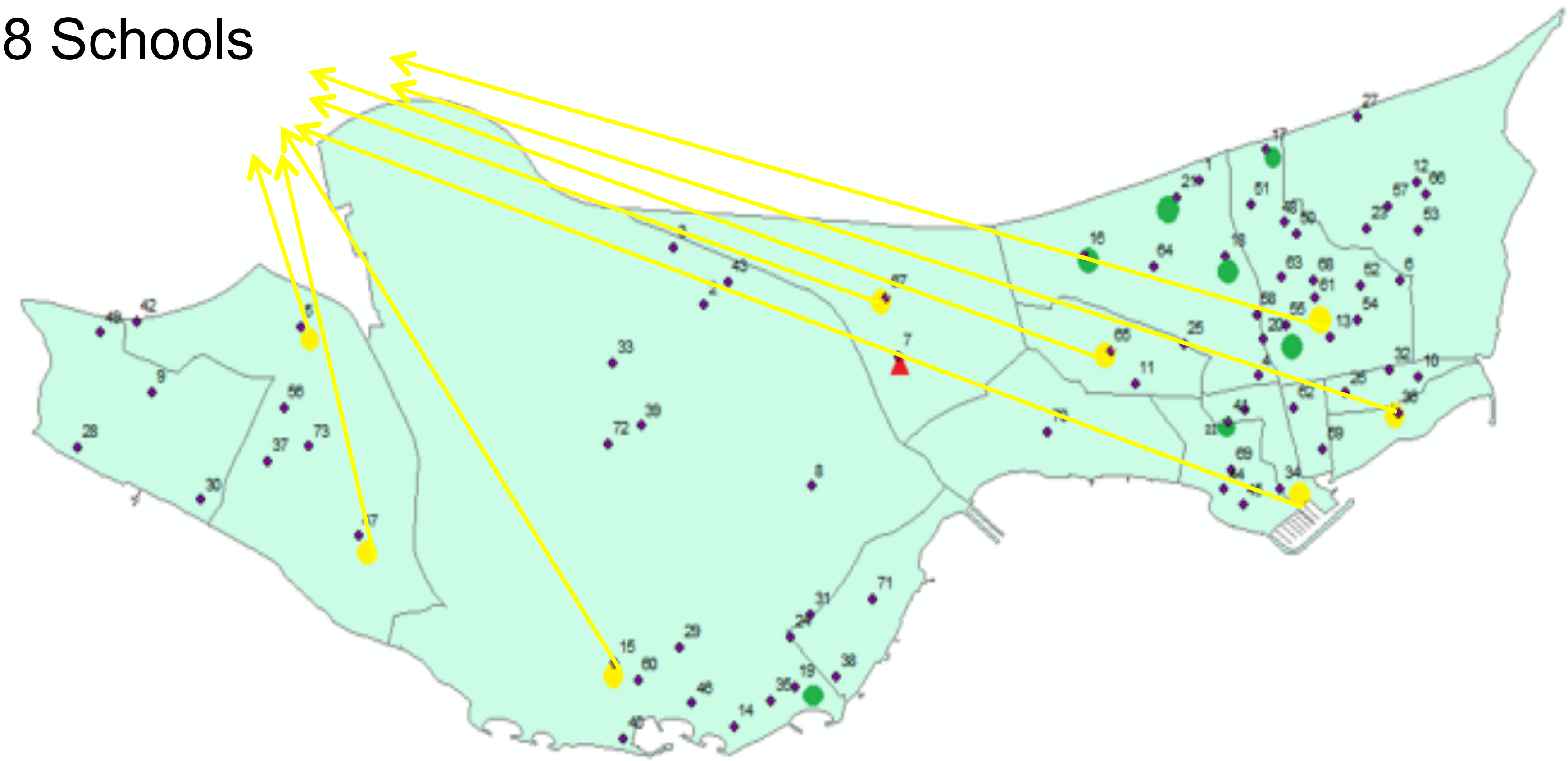


# Data and Computational Results



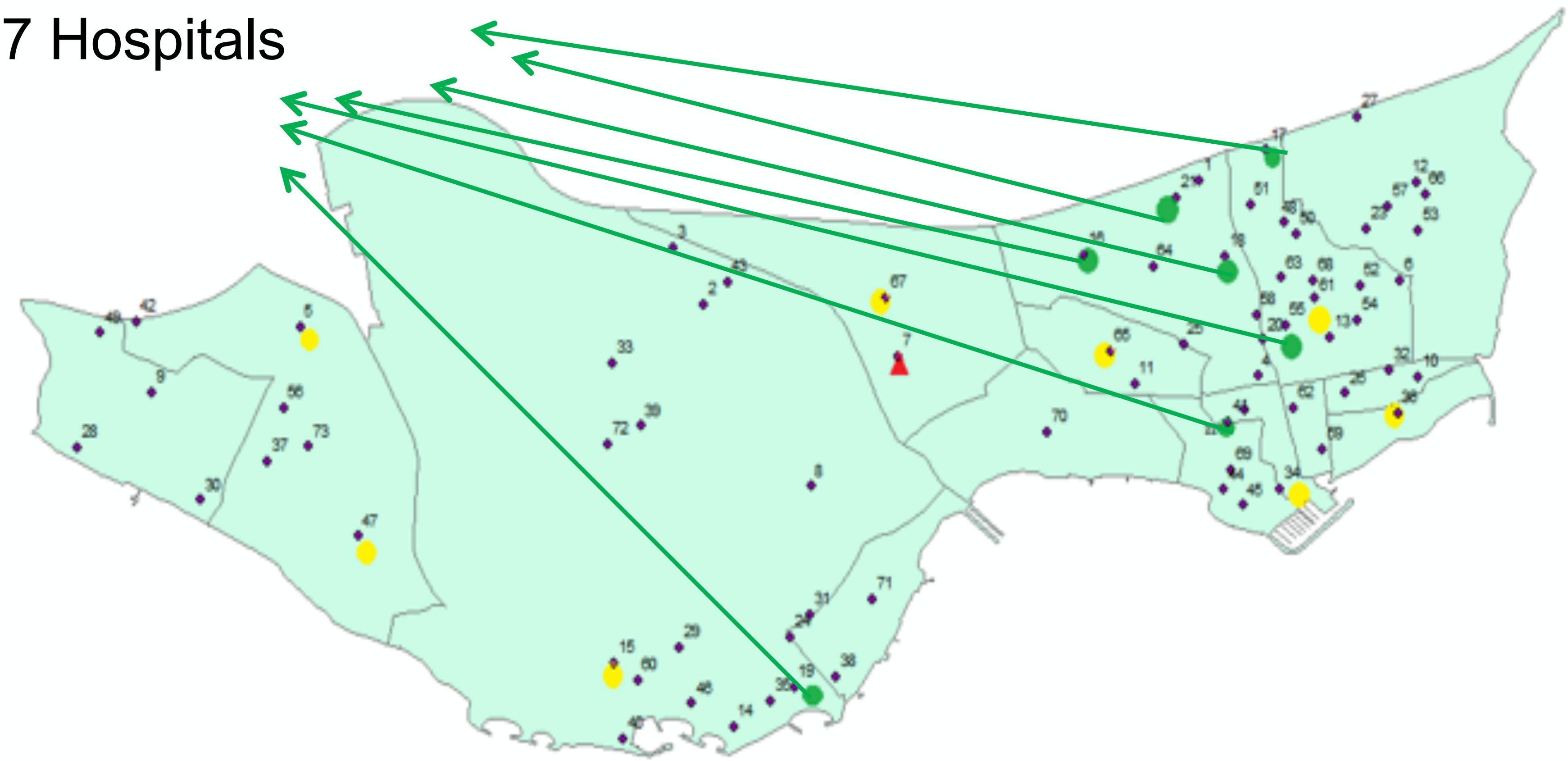
# Data and Computational Results

8 Schools



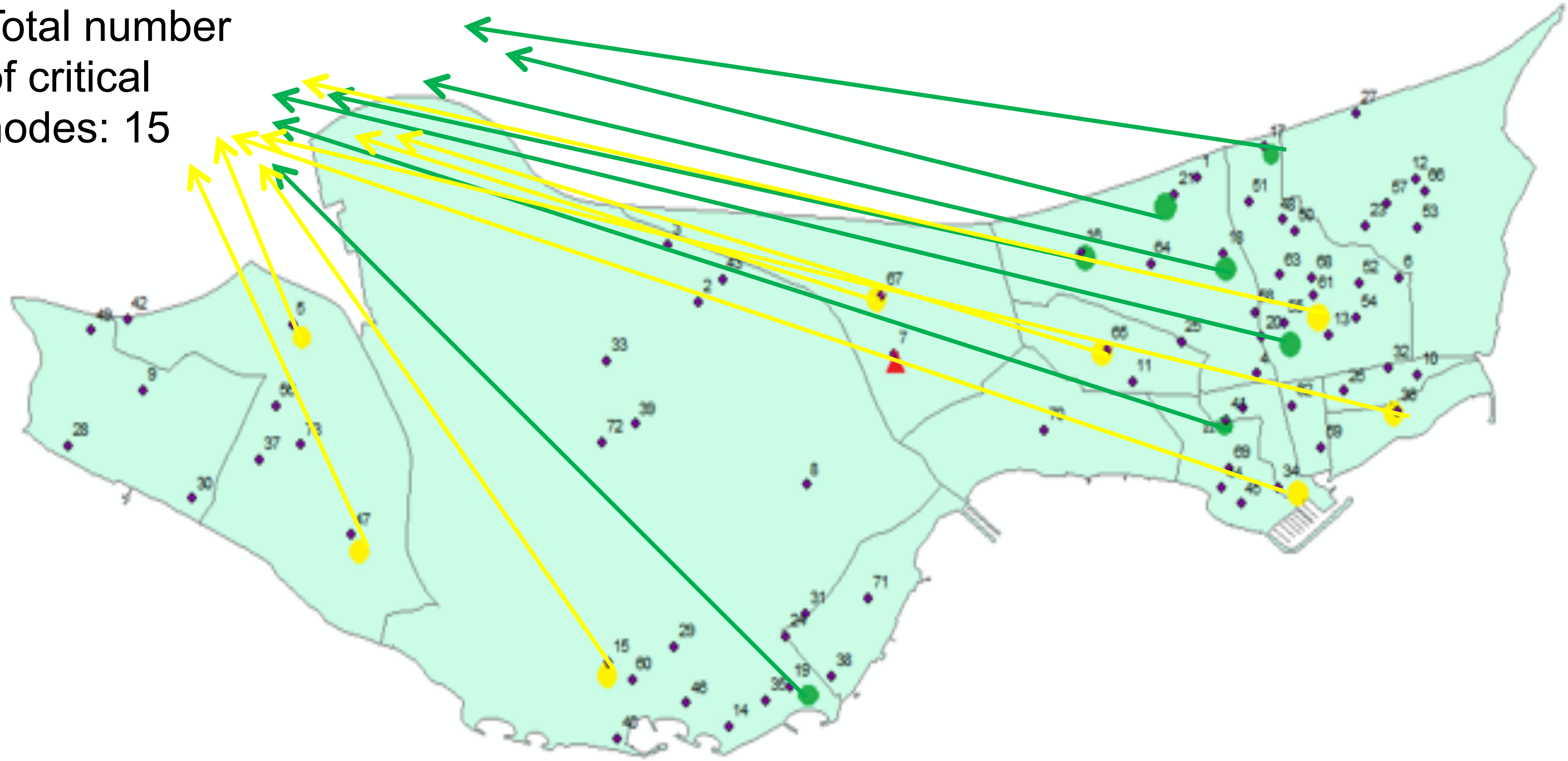
# Data and Computational Results

7 Hospitals



# Data and Computational Results

Total number of critical nodes: 15



# Computational Analysis for Kartal

- As SOE ↑~ # of blocked arcs ↑
  - Becomes compulsory to unblock arcs in order to visit critical nodes for some instances with greater SOE.

SOE=1 | SOE=2

| instances: K-1…K-5 | | | | instances: K-6…K-10 | | | |
|---|---|---|---|---|---|---|---|
| #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs | #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs |
| 7(all) | 44 | 221.41 | - | 7(all) | 48 | 223.26 | - |
| | 43 | 186.73 | - | | 50 | 235.96 | - |
| | 44 | 190.82 | - | | 51 | 270.41 | - |
| | 43 | 178.4 | - | | 49 | 225.46 | - |
| | 43 | 183.2 | - | | 48 | 261.39 | - |
| 4(hospitals) | 35 | 8.81 | - | 4(hospitals) | 38 | 15.39 | - |
| | 35 | 10.02 | - | | 42 | 8.4 | - |
| | 36 | 6.27 | - | | 40 | 9.09 | - |
| | 35 | 12.08 | - | | 42 | 10.75 | - |
| | 35 | 11.69 | - | | 39 | 7.04 | - |
| 3(schools) | 30 | 1.4 | - | 3(schools) | 29 | 2.52 | - |
| | 30 | 1.47 | - | | 29 | 2.54 | - |
| | 30 | 1.61 | - | | 30 | 2.28 | - |
| | 29 | 1.44 | - | | 35 | 3.51 | - |
| | 29 | 1.44 | - | | 30 | 3.04 | - |

SOE=3 | SOE=4

| instances: K-11…K-15 | | | | instances: K-16…K-20 | | | |
|---|---|---|---|---|---|---|---|
| #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs | #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs |
| 7(all) | 53 | 315.37 | - | 7(all) | 109 | 5167.18 | (21,22) |
| | 63 | 495.63 | - | | 82 | 3319.8 | - |
| | 68 | 381.4 | - | | 110 | 9136.87 | (21,22) |
| | 46 | 196.96 | - | | 90 | 2915.86 | (21,22) |
| | 47 | 186.72 | - | | 101 | 4541.84 | (21,22),(22,41),(33,43) |
| 4(hospitals) | 35 | 4.87 | - | 4(hospitals) | 84 | 22.32 | - |
| | 53 | 9.51 | - | | 67 | 20.23 | - |
| | 51 | 8.32 | - | | 70 | 38.91 | (33,43) |
| | 38 | 8.69 | - | | 70 | 49.49 | - |
| | 40 | 8.41 | - | | 88 | 64.54 | - |
| 3(schools) | 40 | 4.34 | - | 3(schools) | 57 | 6.62 | (21,22) |
| | 35 | 2.98 | - | | 55 | 4.66 | - |
| | 30 | 3.11 | - | | 68 | 7.08 | (21,22) |
| | 35 | 2.85 | - | | 55 | 4.76 | (21,22) |
| | 29 | 2.51 | - | | 45 | 3.62 | (21,22) |

# Computational Analysis

- Identical instances with different debris removal effort requirements
  - Not hesitated to travel on a path that includes blocked arcs on the drive when the required effort is less.

Wij: Greater debris removal effort

| instances: K-11…K-15 | | | |
|---|---|---|---|
| #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs |
| 7(all) | 53 | 315.37 | - |
| | 63 | 495.63 | - |
| | 68 | 381.4 | - |
| | 46 | 196.96 | - |
| | 47 | 186.72 | - |
| 4(hospitals) | 35 | 4.87 | - |
| | 53 | 9.51 | - |
| | 51 | 8.32 | - |
| | 38 | 8.69 | - |
| | 40 | 8.41 | - |
| 3(schools) | 40 | 4.34 | - |
| | 35 | 2.98 | - |
| | 30 | 3.11 | - |
| | 35 | 2.85 | - |
| | 29 | 2.51 | - |

| instances: K-16…K-20 | | | |
|---|---|---|---|
| #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs |
| 7(all) | 109 | 5167.18 | (21,22) |
| | 82 | 3319.8 | - |
| | 110 | 9136.87 | (21,22) |
| | 90 | 2915.86 | (21,22) |
| | 101 | 4541.84 | (21,22),(22,41),(33,43) |
| 4(hospitals) | 84 | 22.32 | - |
| | 67 | 20.23 | - |
| | 70 | 38.91 | (33,43) |
| | 70 | 49.49 | - |
| | 88 | 64.54 | - |
| 3(schools) | 57 | 6.62 | (21,22) |
| | 55 | 4.66 | - |
| | 68 | 7.08 | (21,22) |
| | 55 | 4.76 | (21,22) |
| | 45 | 3.62 | (21,22) |

Wij': Smaller debris removal effort

| instances: K-11'…K-15' | | | |
|---|---|---|---|
| #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs |
| 7(all) | 51 | 214.86 | (21,22) |
| | 63 | 316.91 | - |
| | 67 | 336.34 | (27,33) |
| | 46 | 198.85 | - |
| | 47 | 184.67 | - |
| 4(hospitals) | 35 | 7.84 | - |
| | 53 | 8.37 | - |
| | 50 | 16.5 | (33,43) |
| | 38 | 9.42 | - |
| | 40 | 13.71 | - |
| 3(schools) | 38 | 3.42 | (21,22) |
| | 33 | 3.12 | (21,22) |
| | 30 | 2.93 | - |
| | 35 | 2.03 | - |
| | 29 | 2.65 | - |

| instances: K-16'…K-20' | | | |
|---|---|---|---|
| #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs |
| 7(all) | 97 | 4864.74 | (3,26),(21,22),(43,45) |
| | 78 | 2422.78 | (22,41) |
| | 95 | 3791.44 | (14,15),(21,22),(33,43) |
| | 81 | 2794.34 | (21,22),(43,45) |
| | 80 | 3258.78 | (21,22),(22,41),(33,43) |
| 4(hospitals) | 80 | 54.89 | (16,32),(43,45) |
| | 67 | 17.18 | (22,41) |
| | 63 | 32.48 | (33,43) |
| | 70 | 26.91 | - |
| | 73 | 14.96 | (21,22),(22,41),(33,43) |
| 3(schools) | 50 | 4.88 | (21,22) |
| | 51 | 3.48 | (21,22) |
| | 61 | 5.24 | (21,22) |
| | 48 | 4.73 | (21,22) |
| | 38 | 4.51 | (21,22) |

# Computational Analysis

- CPU times
  - # of critical nodes
    - Affects dramatically!
    - As the # of critical nodes increases, the CPU times exponentially increase.

| #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs | #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs |
|---|---|---|---|---|---|---|---|
| instances: K-1…K-5 | | | | instances: K-6…K-10 | | | |
| 7(all) | 44 | 221.41 | - | 7(all) | 48 | 223.26 | - |
| | 43 | 186.73 | - | | 50 | 235.96 | - |
| | 44 | 190.82 | - | | 51 | 270.41 | - |
| | 43 | 178.4 | - | | 49 | 225.46 | - |
| | 43 | 183.2 | - | | 48 | 261.39 | - |
| 4(hospitals) | 35 | 8.81 | - | 4(hospitals) | 38 | 15.39 | - |
| | 35 | 10.02 | - | | 42 | 8.4 | - |
| | 36 | 6.27 | - | | 40 | 9.09 | - |
| | 35 | 12.08 | - | | 42 | 10.75 | - |
| | 35 | 11.69 | - | | 39 | 7.04 | - |
| 3(schools) | 30 | 1.4 | - | 3(schools) | 29 | 2.52 | - |
| | 30 | 1.47 | - | | 29 | 2.54 | - |
| | 30 | 1.61 | - | | 30 | 2.28 | - |
| | 29 | 1.44 | - | | 35 | 3.51 | - |
| | 29 | 1.44 | - | | 30 | 3.04 | - |

| #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs | #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs |
|---|---|---|---|---|---|---|---|
| instances: K-11…K-15 | | | | instances: K-16…K-20 | | | |
| 7(all) | 53 | 315.37 | - | 7(all) | 109 | 5167.18 | (21,22) |
| | 63 | 495.63 | - | | 82 | 3319.8 | - |
| | 68 | 381.4 | - | | 110 | 9136.87 | (21,22) |
| | 46 | 196.96 | - | | 90 | 2915.86 | (21,22) |
| | 47 | 186.72 | - | | 101 | 4541.84 | (21,22),(22,41),(33,43) |
| 4(hospitals) | 35 | 4.87 | - | | | | |
| | 53 | 9.51 | - | 4(hospitals) | 84 | 22.32 | - |
| | 51 | 8.32 | - | | 67 | 20.23 | - |
| | 38 | 8.69 | - | | 70 | 38.91 | (33,43) |
| | 40 | 8.41 | - | | 70 | 49.49 | - |
| 3(schools) | 40 | 4.34 | - | | 88 | 64.54 | - |
| | 35 | 2.98 | - | 3(schools) | 57 | 6.62 | (21,22) |
| | 30 | 3.11 | - | | 55 | 4.66 | - |
| | 35 | 2.85 | - | | 68 | 7.08 | (21,22) |
| | 29 | 2.51 | - | | 55 | 4.76 | (21,22) |
| | | | | | 45 | 3.62 | (21,22) |

# Computational Analysis

- CPU times
  - For more severe earthquakes, higher CPU values.

SOE=1

SOE=2

| instances: K-1'...K-5' | | | | instances: K-6'...K-10' | | | |
|---|---|---|---|---|---|---|---|
| #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs | #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs |
| 7(all) | 44 | 219.89 | - | 7(all) | 48 | 231.4 | - |
| | 43 | 213.25 | - | | 49 | 210.34 | (33,43) |
| | 44 | 192.61 | - | | 51 | 282.31 | - |
| | 43 | 156.37 | - | | 49 | 259.62 | - |
| | 43 | 152.9 | - | | 48 | 210.25 | - |
| 4(hospitals) | 35 | 7.16 | - | 4(hospitals) | 38 | 9.2 | - |
| | 35 | 10.12 | - | | 41 | 12.63 | (33,43) |
| | 36 | 9.98 | - | | 40 | 10.28 | - |
| | 35 | 7.02 | - | | 42 | 13.18 | - |
| | 35 | 7.31 | - | | 39 | 20.43 | - |
| 3(schools) | 30 | 2.37 | - | 3(schools) | 29 | 1.57 | - |
| | 30 | 1.77 | - | | 29 | 2.75 | - |
| | 30 | 2.76 | - | | 30 | 3.38 | - |
| | 29 | 1.86 | - | | 32 | 3.8 | (21,22) |
| | 29 | 1.85 | - | | 30 | 1.9 | - |

SOE=3

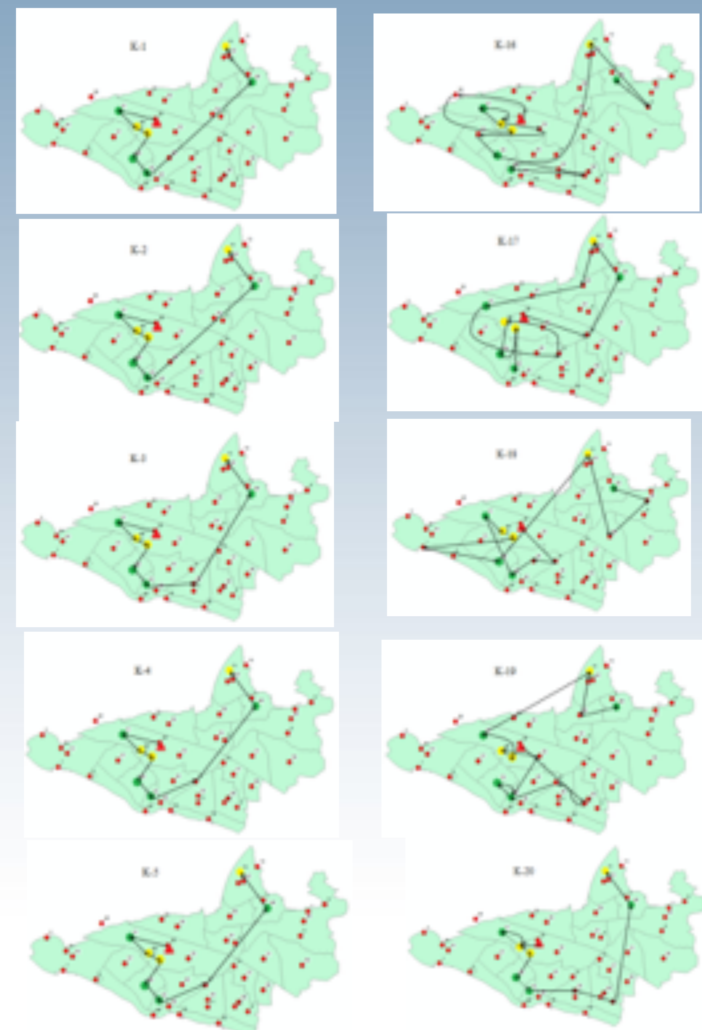
SOE=4

| instances: K-11'...K-15' | | | | instances: K-16'...K-20' | | | |
|---|---|---|---|---|---|---|---|
| #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs | #of critical nodes | Best Objective | cplex CPU(sec) | Debris removed arcs |
| 7(all) | 51 | 214.86 | (21,22) | 7(all) | 97 | 4864.74 | (3,26),(21,22),(43,45) |
| | 63 | 316.91 | - | | 78 | 2422.78 | (22,41) |
| | 67 | 336.34 | (27,33) | | 95 | 3791.44 | (14,15),(21,22),(33,43) |
| | 46 | 198.85 | - | | 81 | 2794.34 | (21,22),(43,45) |
| | 47 | 184.67 | - | | 80 | 3258.78 | (21,22),(22,41),(33,43) |
| 4(hospitals) | 35 | 7.84 | - | 4(hospitals) | 80 | 54.89 | (16,32),(43,45) |
| | 53 | 8.37 | - | | 67 | 17.18 | (22,41) |
| | 50 | 16.5 | (33,43) | | 63 | 32.48 | (33,43) |
| | 38 | 9.42 | - | | 70 | 26.91 | - |
| | 40 | 13.71 | - | | 73 | 14.96 | (21,22),(22,41),(33,43) |
| 3(schools) | 38 | 3.42 | (21,22) | 3(schools) | 50 | 4.88 | (21,22) |
| | 33 | 3.12 | (21,22) | | 51 | 3.48 | (21,22) |
| | 30 | 2.93 | - | | 61 | 5.24 | (21,22) |
| | 35 | 2.03 | - | | 48 | 4.73 | (21,22) |
| | 29 | 2.65 | - | | 38 | 4.51 | (21,22) |

# Computational Analysis

- Resulting travel paths for the instances
  - Same # of blocked arcs
  - With different locations

- **Generally**
  - For less severe earthquakes
    - locations of critical nodes are more important than the number of the critical nodes
      - Order of visit of critical nodes same
  - For more severe earthquakes
    - Order of visit of critical nodes differs a lot



# Computational Analysis

- Similar arguments are valid for Bakırköy
- As the data set becomes larger
  - Difficult to find optimum for some instances
    - Higher |DL|
    - Higher SOE
- Heuristics are developed

- Heuristic:
- Solution times
  - < seconds
- Constructive
- 2-opt

Thank you ☺