Università degli Studi dell'Aquila
Department of Information Engineering, Computer Science and Mathematics

PhD in Information and Communication Technologies

Optimization Models for Pedestrian Emergency Evacuation Planning

XXXIV Doctoral Cycle

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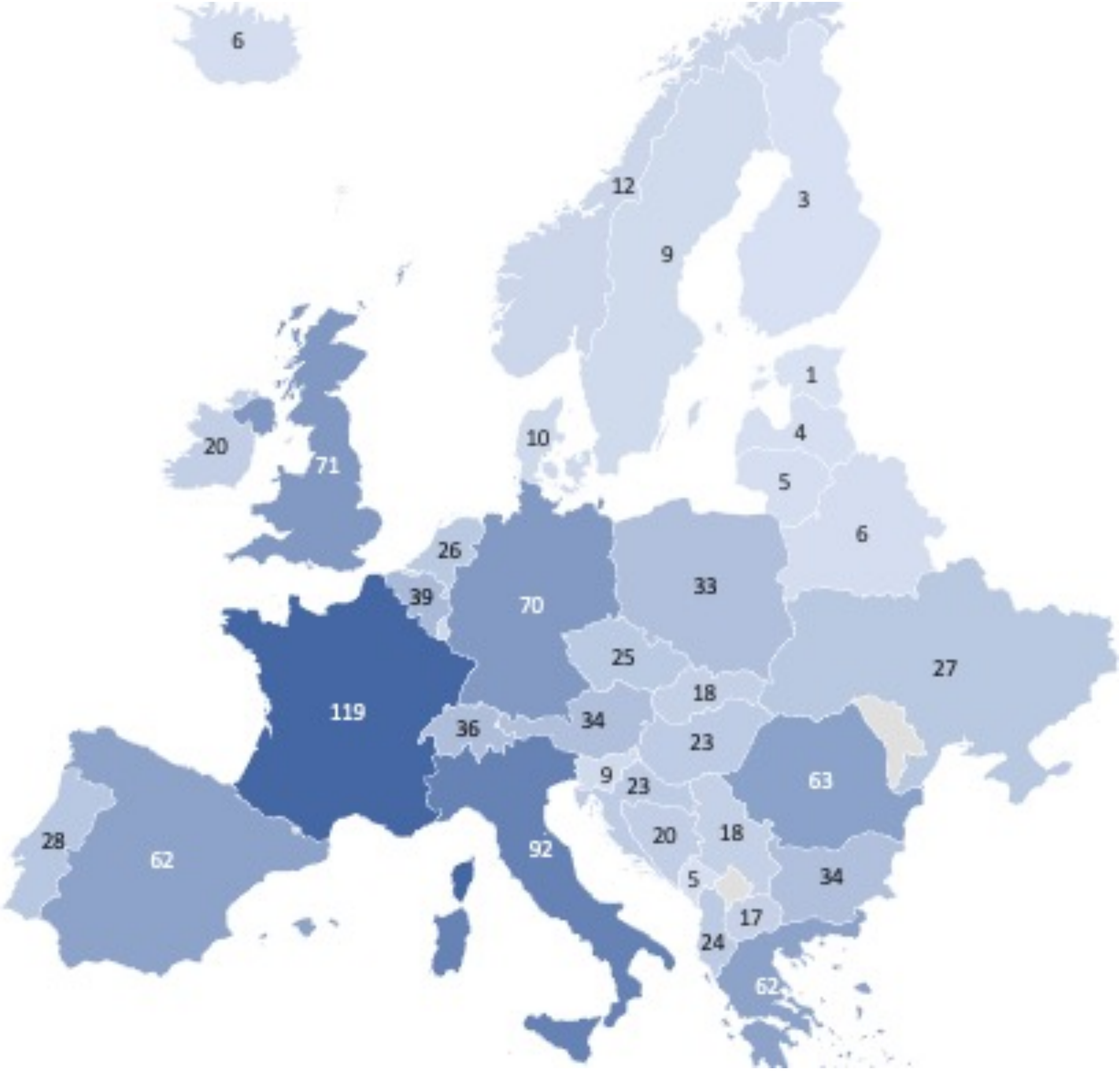
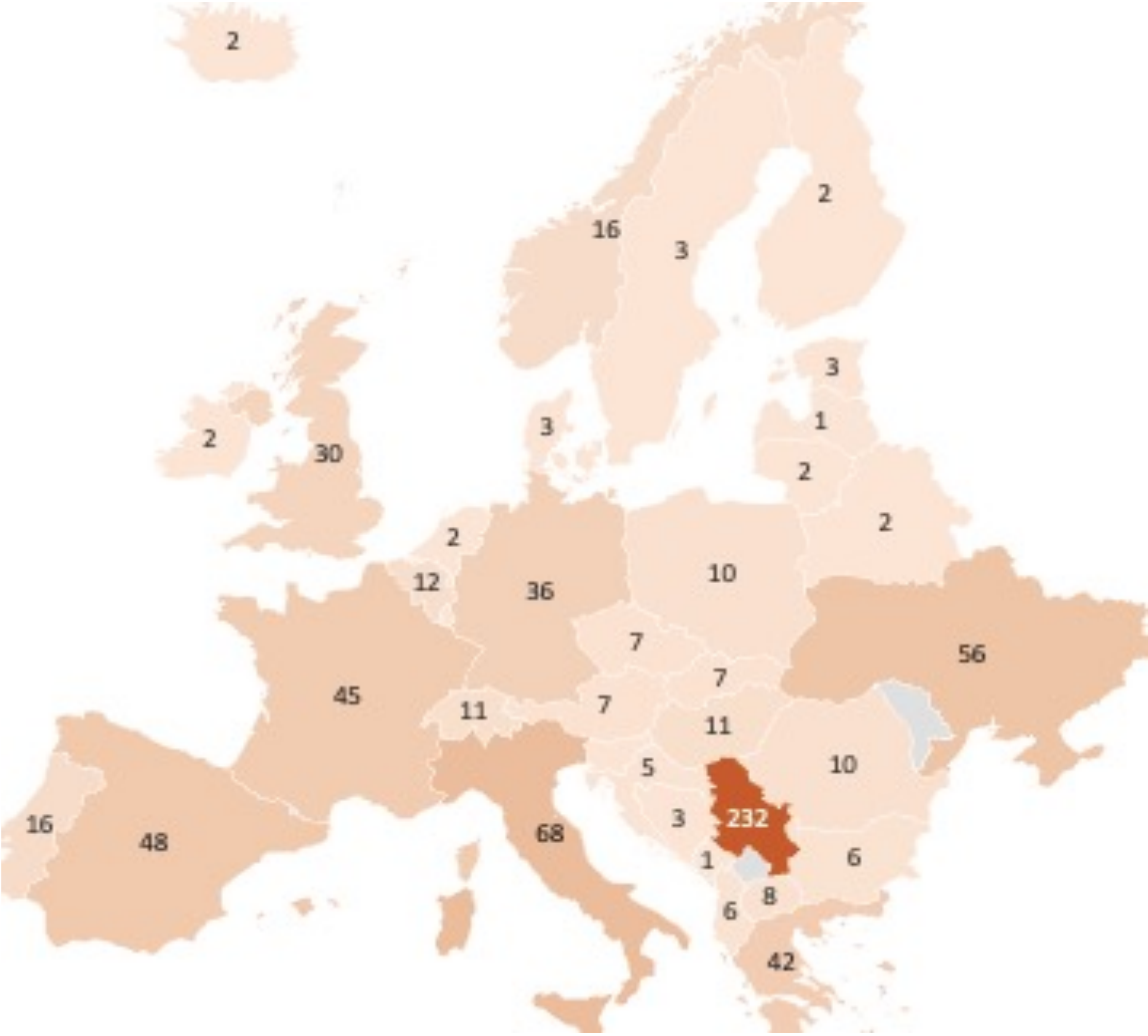
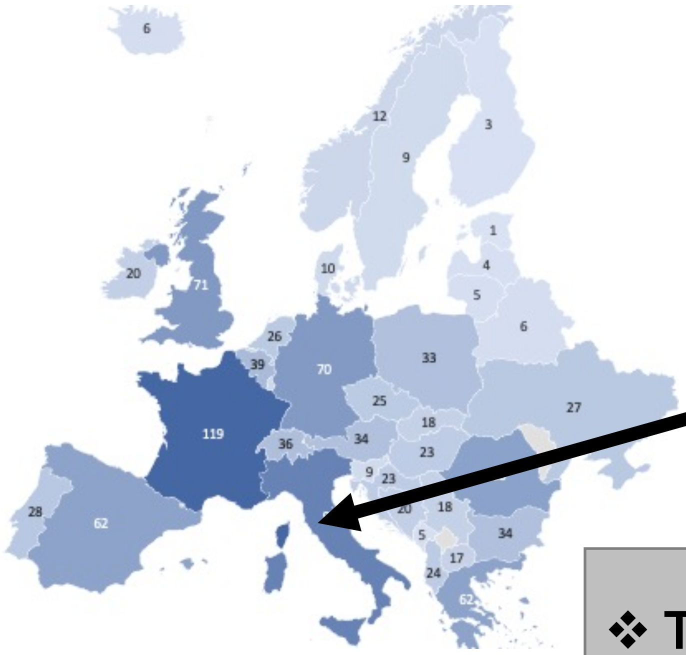
Motivating Scenario: European Occurrences from Disasters (Natural and Technological from 1990 - 2020)

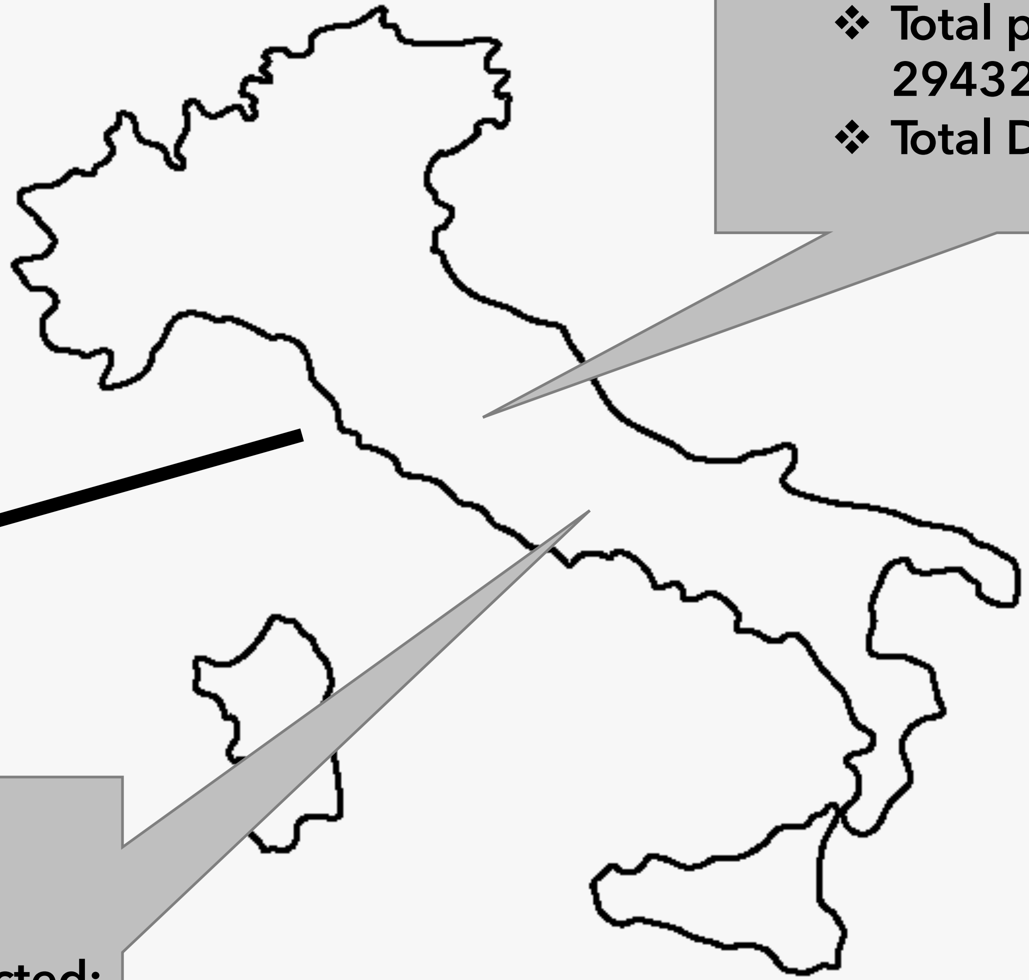


Natural Disasters



Technological Disasters





- Natural
  - Count: 92
  - Total people affected: 294323
  - Total Death: 1249

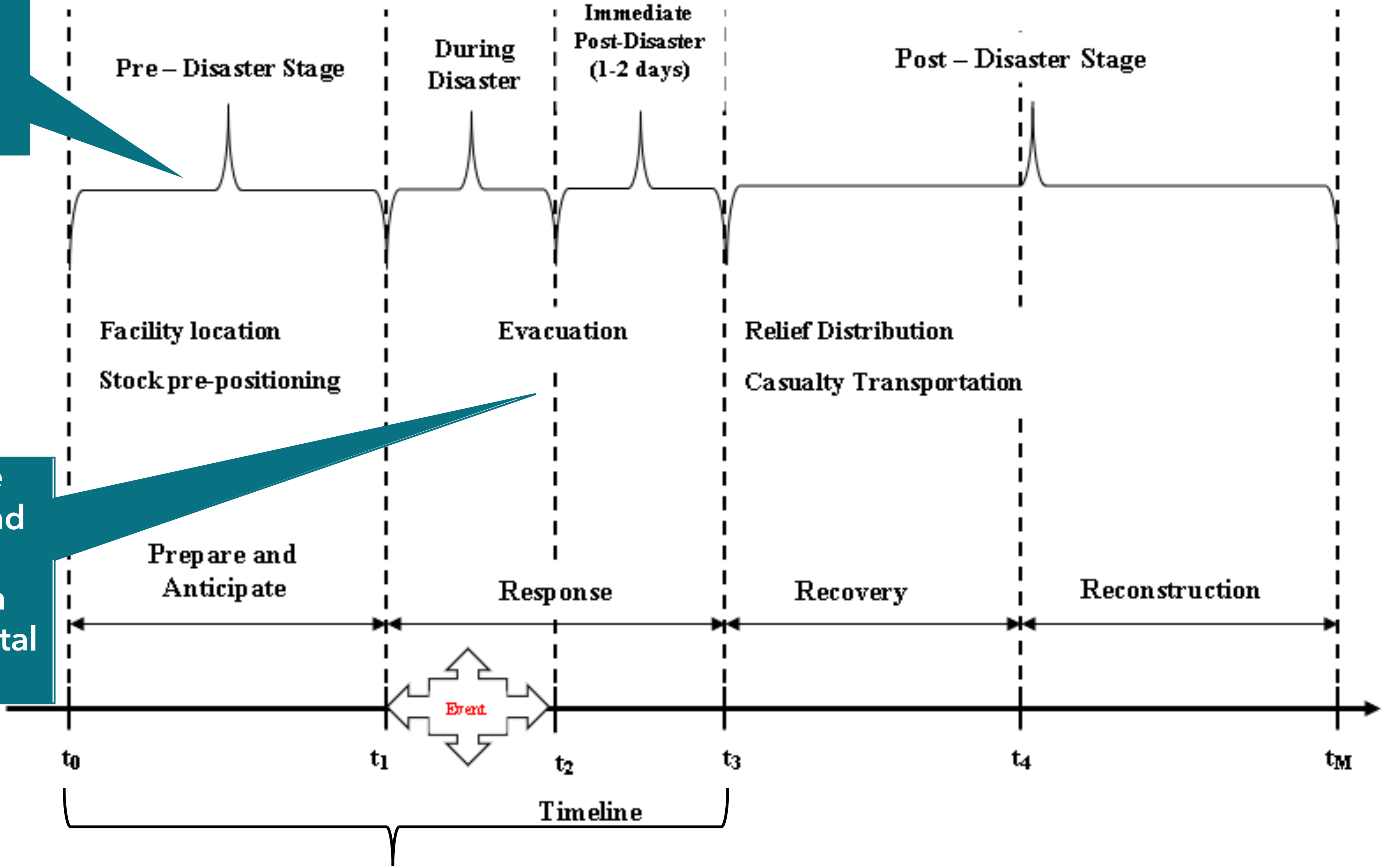
- Technological
  - Count: 68
  - Total people affected: 4953
  - Total Death: 2748

Source: Emergency Events Database

Disaster management

What is the best positioning of the emergency and storage facilities?

How to choose the available shelters and how to define evacuation plans in order to minimize total evacuation times?



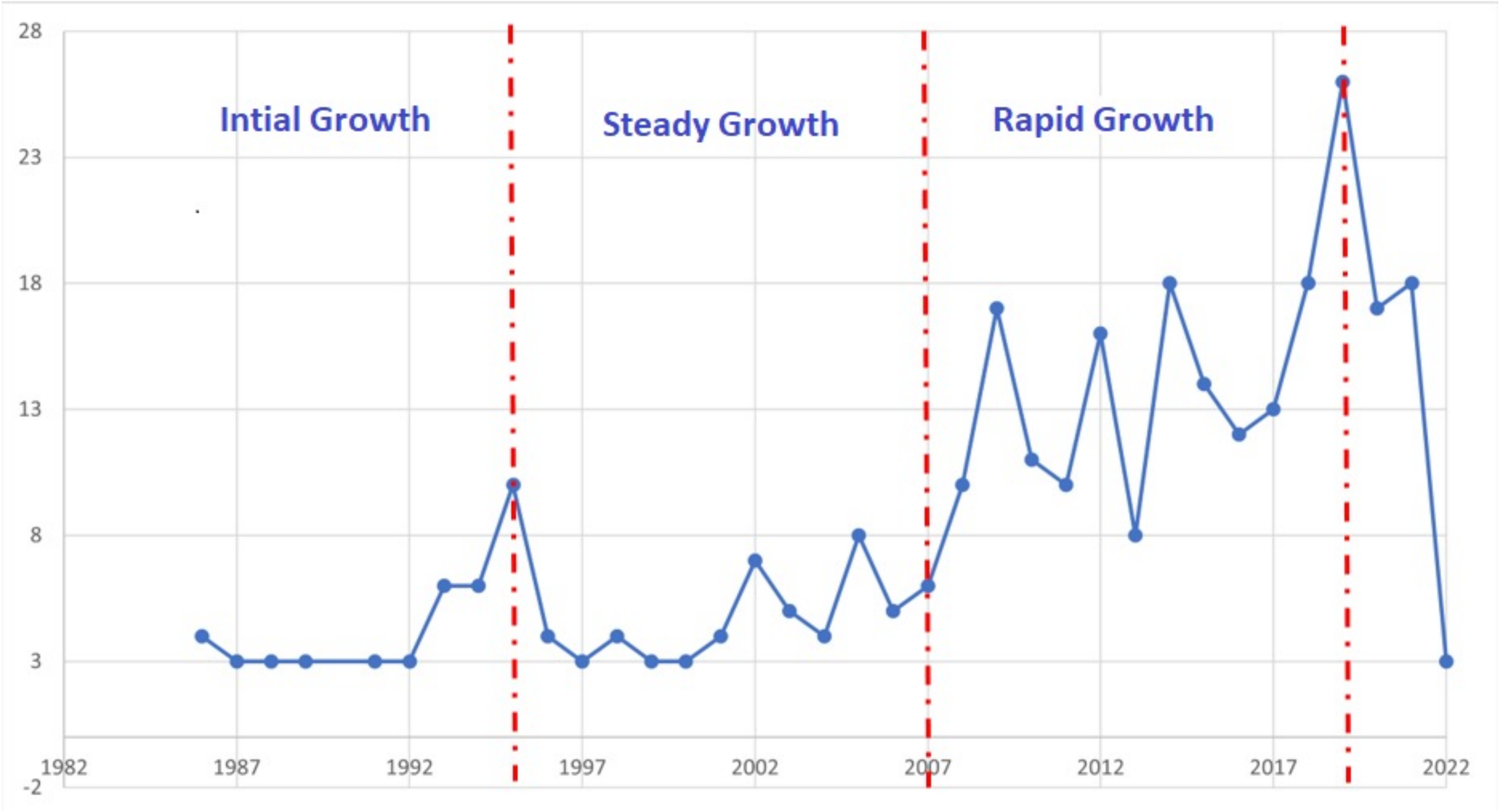
Timeline for research activities

Outline

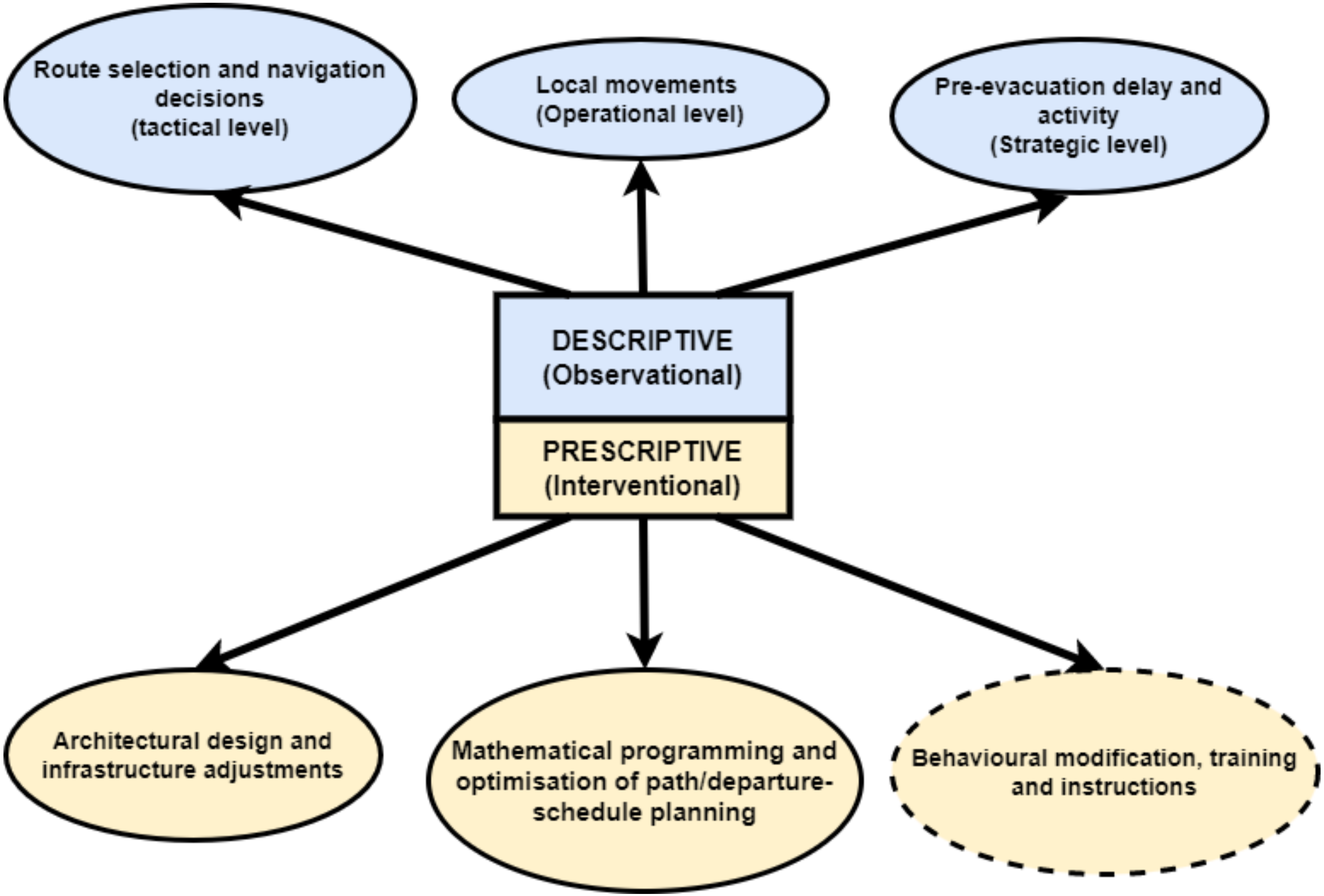
- ❖ Discussion of State-of-the-Art Pedestrian Emergency Models
- ❖ Development of a Network Transformation and Conversion (NTC) model.
- ❖ Formulation of Dynamic Cell Transmission Evacuation Planning (DyCTEP) model
- ❖ Optimal Route Assignment Algorithm (ORAA).
- ❖ Proposal of the Dynamic Earliest Arrival Flow (DEAF)
- ❖ Extension of DyCTEP:
    - ❖ Extended CTM
    - ❖ Multiple Cell Sizes
- ❖ Priority Multi-Party Capacity Constrained Route Planning (PMP-CCRP)
- ❖ Application of models to real-life data

Pedestrian Emergency Evacuation Models: State of the Art

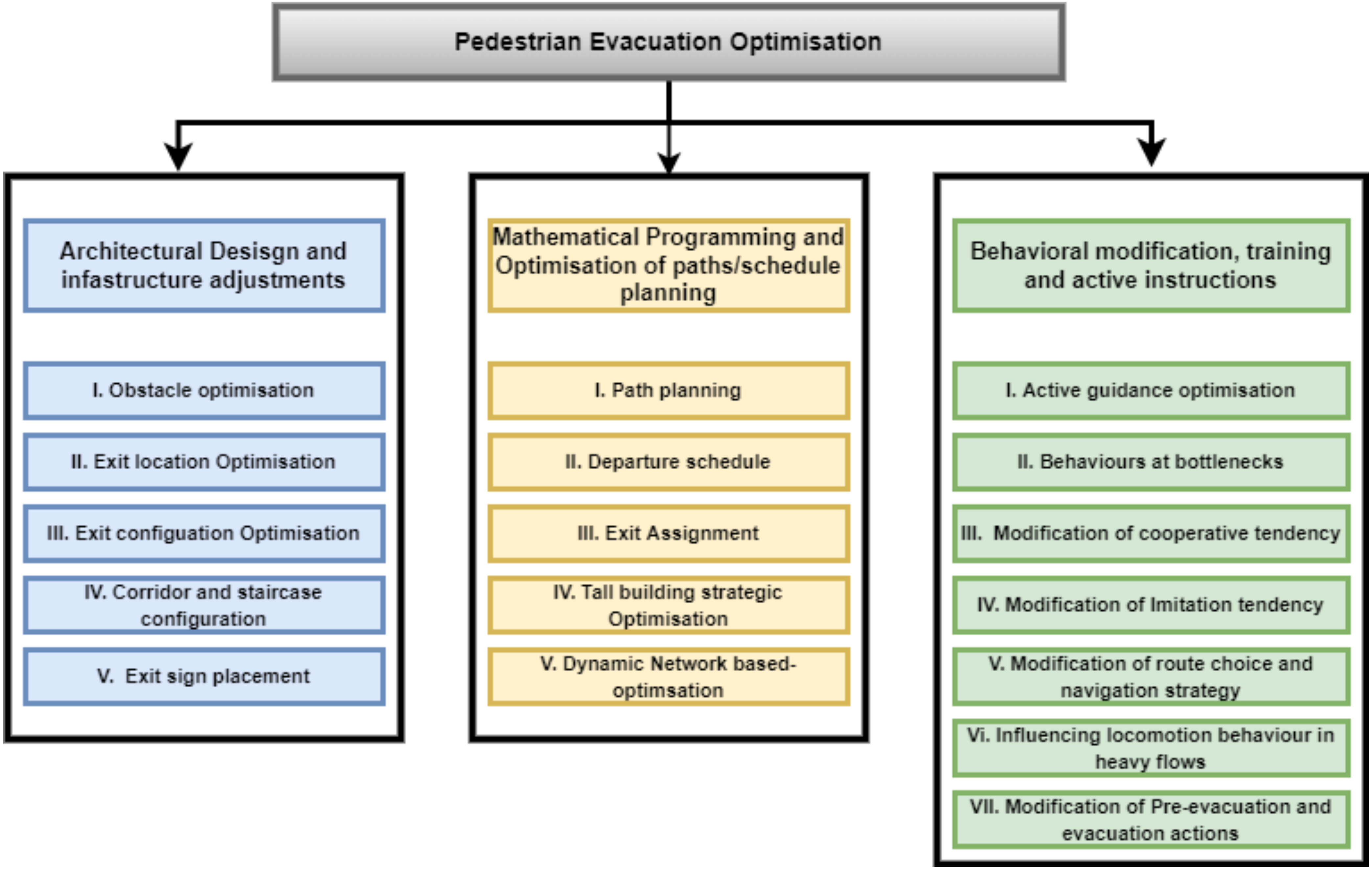
Document type	Count
Article	252
Proceeding Paper	85
Review	31
Meeting Abstract	15
Editorial Material	8
TOTAL	391



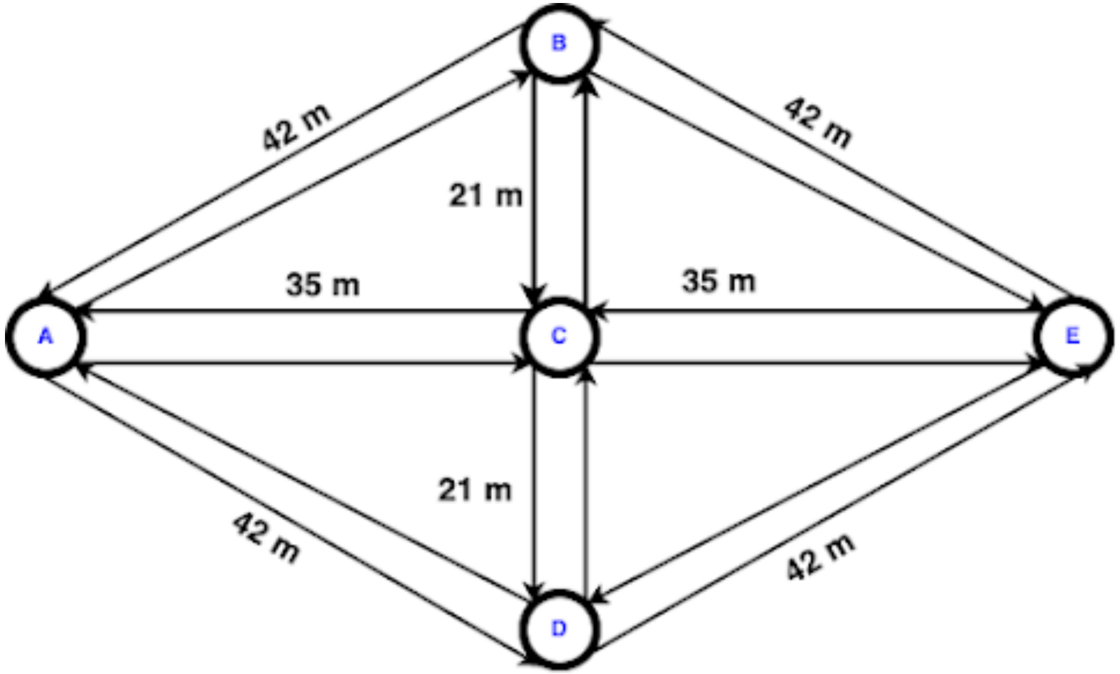
Pedestrian Emergency Evacuation Models: State of the Art

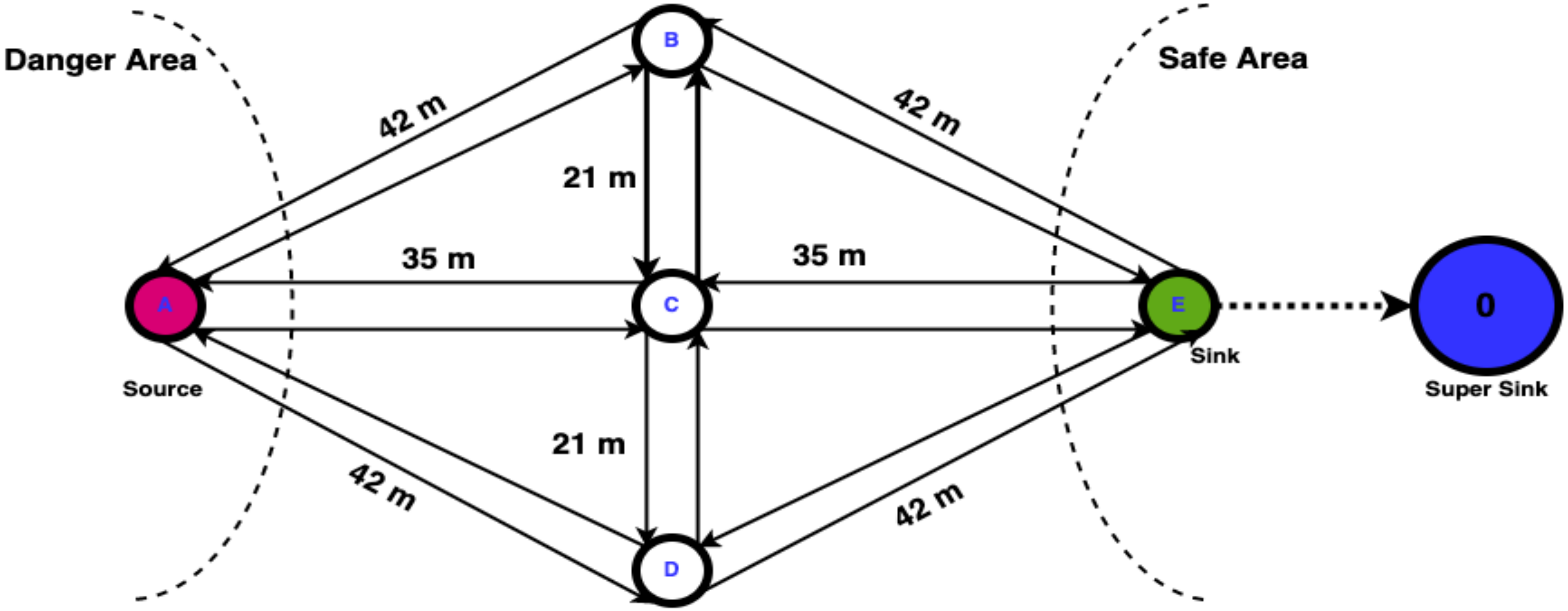


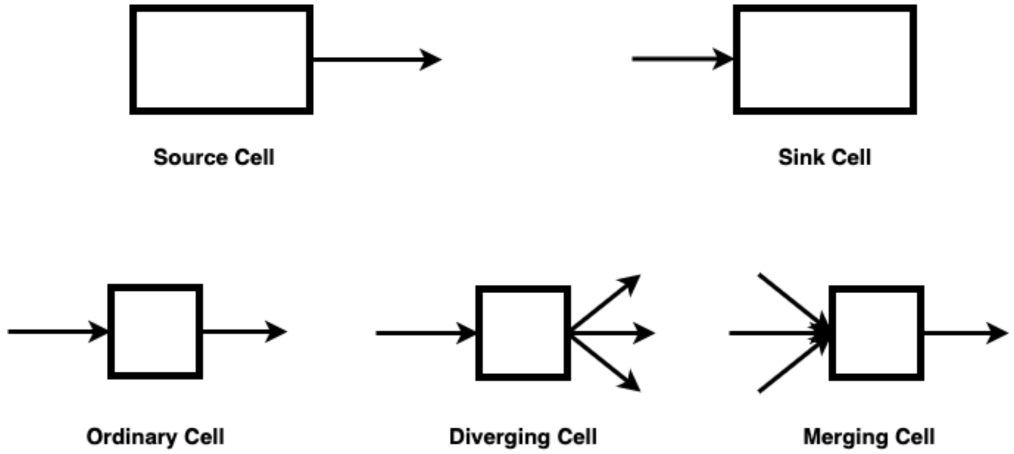
Pedestrian Emergency Evacuation Models: State of the Art



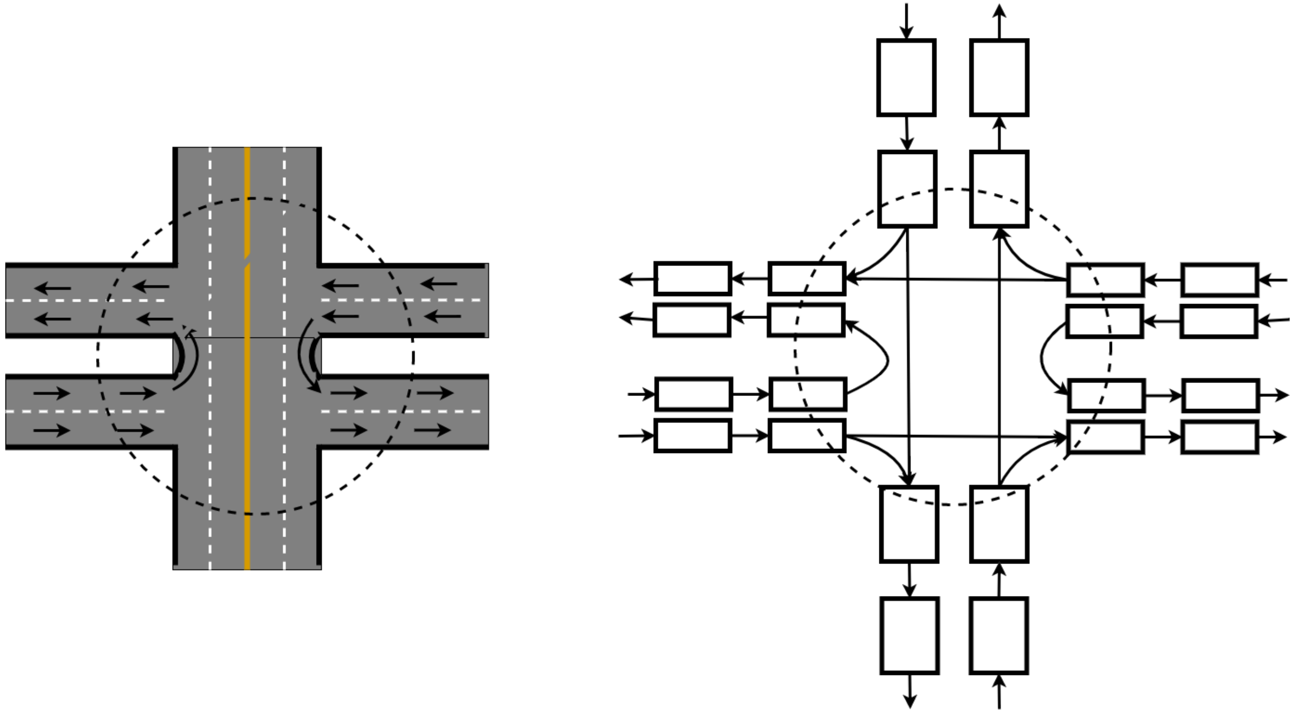
Network Generation



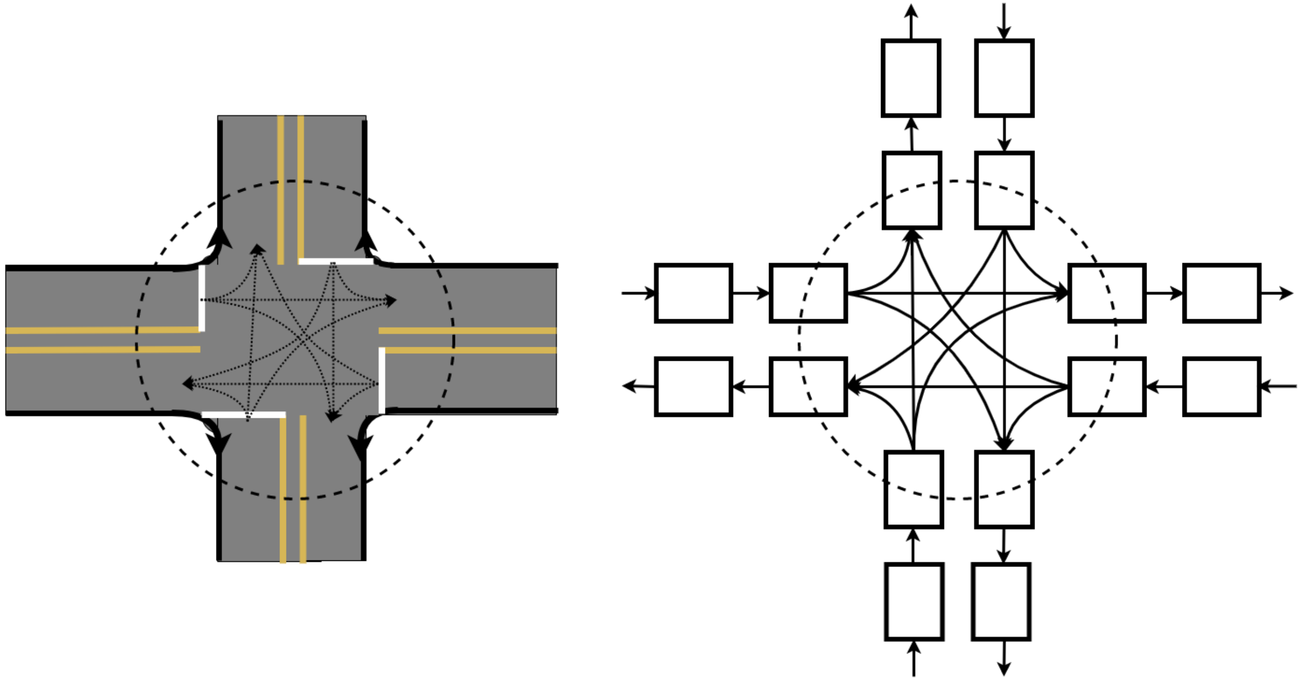




Depiction of the various types of cells used in the model

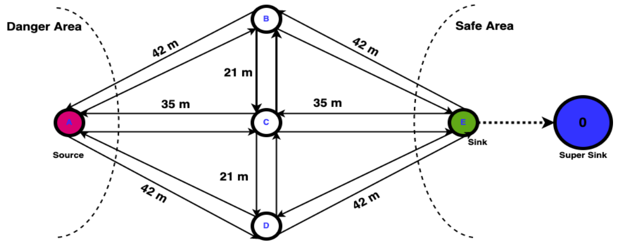


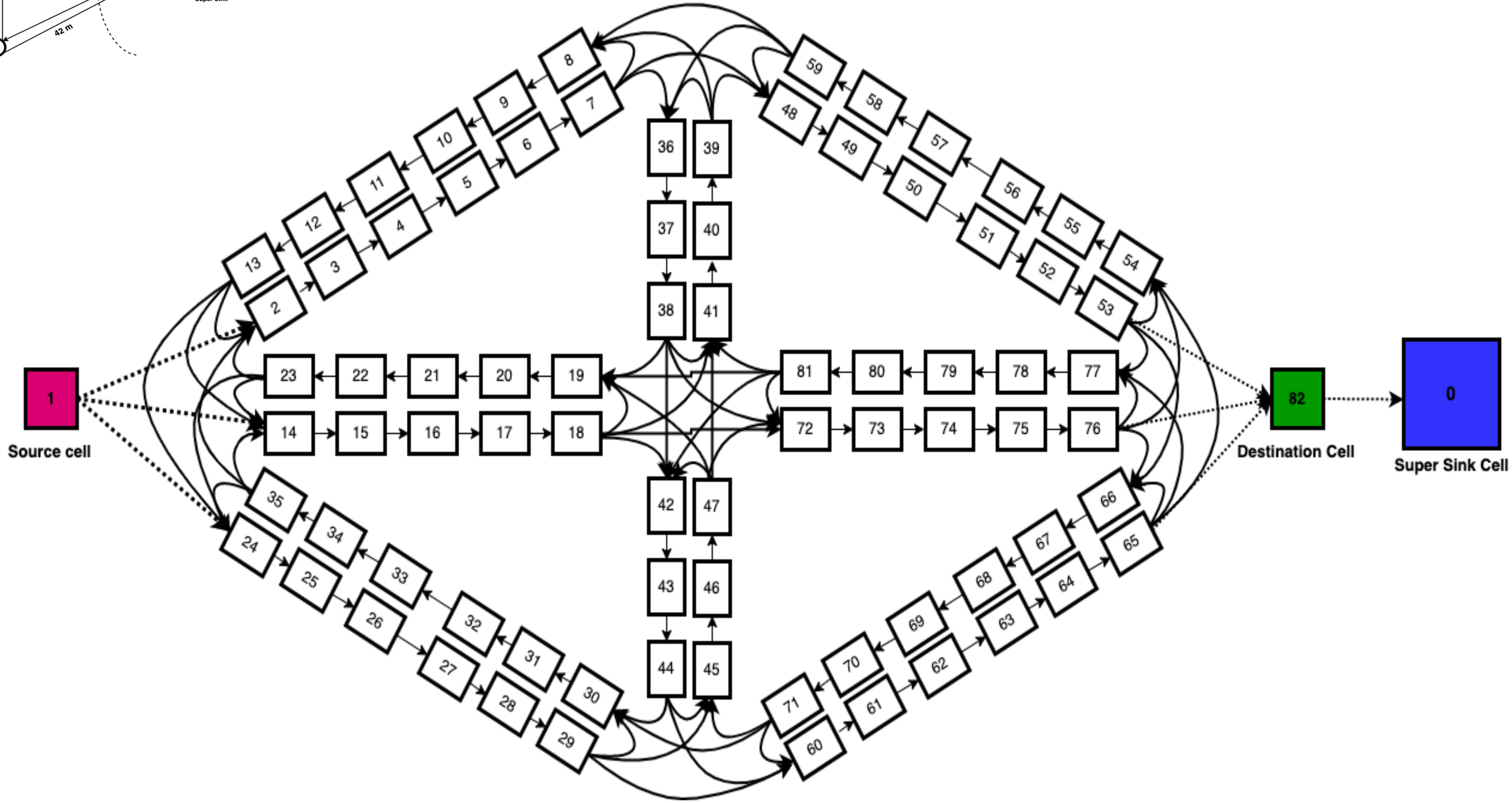
U-turn Node with group of connectors



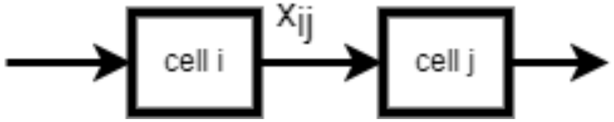
Intersection Node with group of connectors

Transformed network

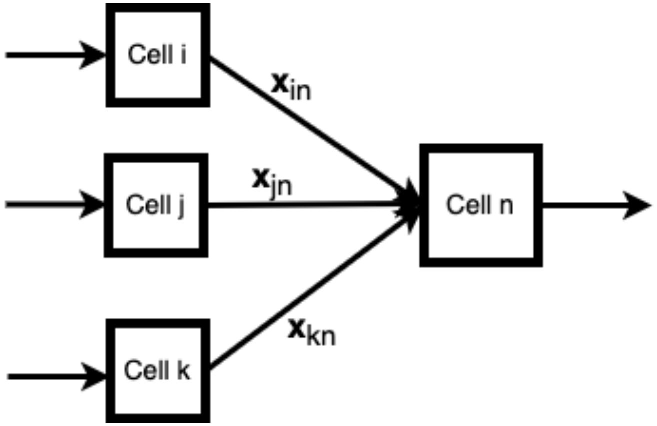




Depiction of various cells types used in the DyCTEP model

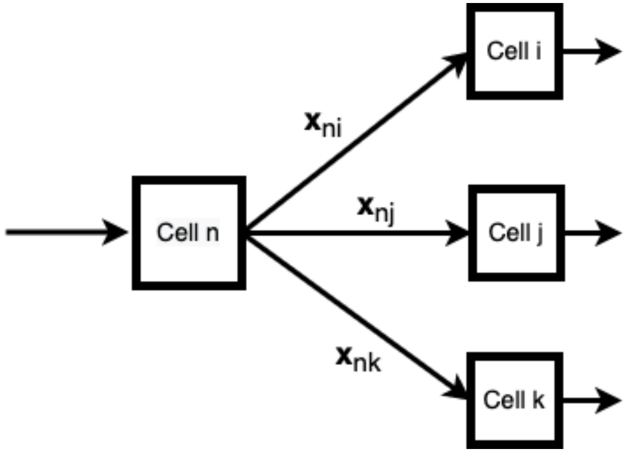


$$x_{ij}^t \le c_{ij}$$



$$x_{in}^t \le S_i;\ x_{jn}^t \le S_j;\ x_{kn}^t \le S_k$$

$$x_{in}^t + x_{jn}^t + x_{kn}^t \le R_n$$



$$x_{ni}^t \le R_i;\ x_{nj}^t \le R_j;\ x_{nk}^t \le R_k$$

$$x_{ni}^t + x_{nj}^t + x_{nk}^t \le S_n$$

Parameters:
$\mathfrak{T}$
V
D
S
0
A
c_{ij}

n_i
v
w
δ_i^t
q_i
$Q_i^t = Q_i$
$\lambda_{ij} = \lambda_{ji}$
Decision Variables:
y_i^t
x_{ij}^t

z_i^{t+1}

$x_{i(k,k+1)}^t$

- **The max ouflow from a cell is constrained by:** $S_j = \min\{y_j^t, Q_j\}$
- **The max inflow to a cell is constrained by:** $R_i = \min\{Q_i, n_i - y_i^t\}$
- **And** $x_{ji}^t = \min\{S_j, R_i\}$
- **Therefore:**
  - $x_{ij}^t = \min\{y_i^t, Q_i, Q_j, (n_j - y_j^t)\}$ ***or*** $x_{ij}^t = \min\{y_i^t, c_{ij}, (n_j - y_j^t)\}$

Dynamic Cell Transmission Evacuation Planning (DyCTEP) model

$$\text{Problem: SO-DTA (CTM)} \; : \min \sum_{t \in \mathfrak{T}} \sum_{i \in V \setminus 0} y_i^t \tag{1.10a}$$

$$y_i^t - y_i^{t-1} - \sum_{j:ji \in A} x_{ji}^{t-1} + \sum_{j:ij \in A} x_{ij}^{t-1} = 0, \quad \forall i \in V \setminus \{S \cup 0\}, t \in T, t > 0 \tag{1.10b}$$

$$y_0^t - y_0^{t-1} - \sum_{j:j0 \in A} x_{j0}^{t-1} = 0, \quad t \in T, t > 0 \tag{1.10c}$$

$$y_i^t - y_i^{t-1} + \sum_{j:ij \in A} x_{ij}^{t-1} = \begin{cases} q_i, & \text{for } t = 1 \\ 0, & \text{for } \forall t > 1 \end{cases}, \quad \forall i \in S \tag{1.10d}$$

$$\sum_{j:ji \in A} x_{ji}^t \le Q_i, \quad \forall i \in V \setminus \{S\}, t \in T \tag{1.10e}$$

$$\sum_{j:ji \in A} x_{ji}^t \le \delta_i (n_i - y_i^t), \quad \forall i \in V \setminus \{S\}, t \in T \tag{1.10f}$$

$$\sum_{j:ij \in A} x_{ij}^t \le Q_i, \quad \forall i \in V \setminus \{0\}, t \in T \tag{1.10g}$$

$$\sum_{j:ij \in A} x_{ij}^t - y_i^t \le 0, \quad \forall i \in V \setminus \{0\}, t \in T \tag{1.10h}$$

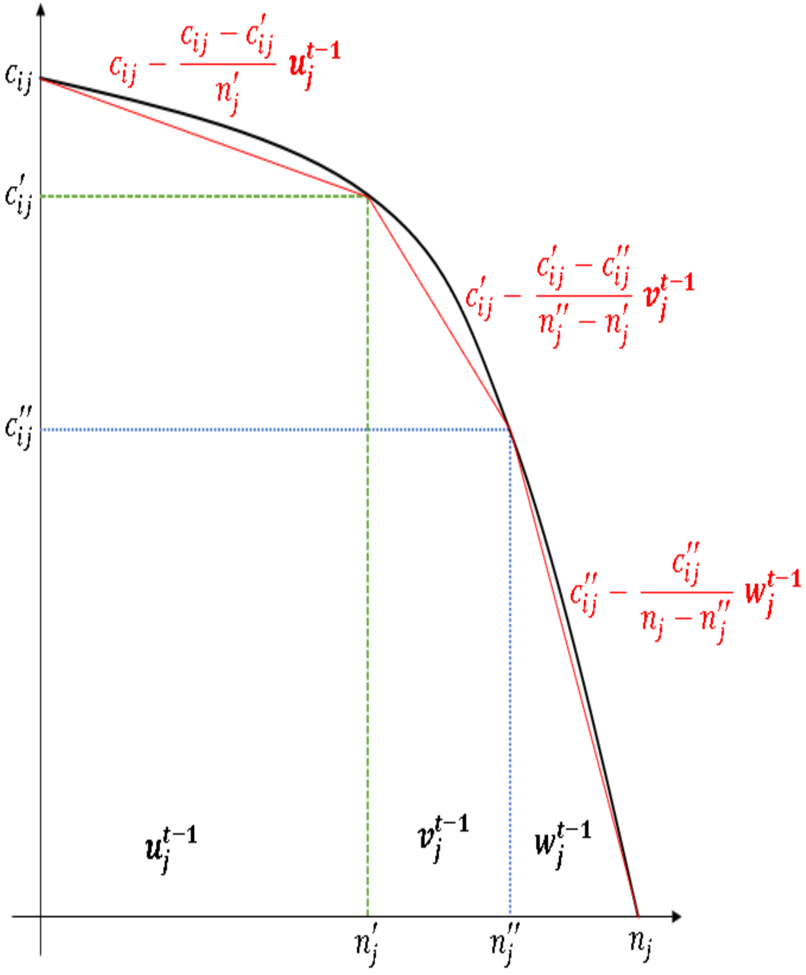
$$0 \le x_{ij}^t + x_{ji}^t \le c_{ij}, \quad \forall (ij) \in A, t \in T \tag{1.10i}$$

$$y_i^0 = 0, \quad \forall i \in V \tag{1.10j}$$

$$x_{ij}^0 = 0, \quad \forall (i,j) \in A \tag{1.10k}$$

Model with congestion

❖ To get a more realistic and accuate model, we take into account congestions at the arc capacities, which is modeled as a concave decreasing function of the cell capacity.



Congestion curve for arc capacity constraints

❖ Linearizing the concavity one can replace constraint (1.10i) with the following:

❖ $y_i^{t-1} = u_i^{t-1} + v_i^{t-1} + w_i^{t-1}$ and $x_{ij}^t = \phi_{ij}^t + \chi_{ij}^t + \psi_{ij}^t$ (*)

❖ Subject to the following non-negative upper bounds

❖ $u_i^{t-1} \le n_i', \;\; v_i^{t-1} \le n_i'' - n_i'$ and $w_i^{t-1} \le n_i - n_i''$ (**)

❖ $0 \le \phi^t{}_{ij} \le c_{ij} - \frac{c_{ij} - c'_{ij}}{n'_j} u_j^{t-1}$

❖ $0 \le \chi_{ij}^t \le c'_{ij} - \frac{c'_{ij} - c''_{ij}}{n''_j - n'_j} v_j^{t-1}$

❖ $0 \le \psi_{ij}^t \le c''_{ij} - \frac{c''_{ij}}{n_j - n''_j} w_j^{t-1}$

(***)

❖ Consistency of the ϕ, χ and ψ variables with the *x* flow variables requires χ = 0 (ψ = 0) if ϕ (if χ) does not saturate its capacity.

❖ This is ensured, at optimality, by the properties of basic solutions.

Optimal Route Assignment Algorithm (ORAA):

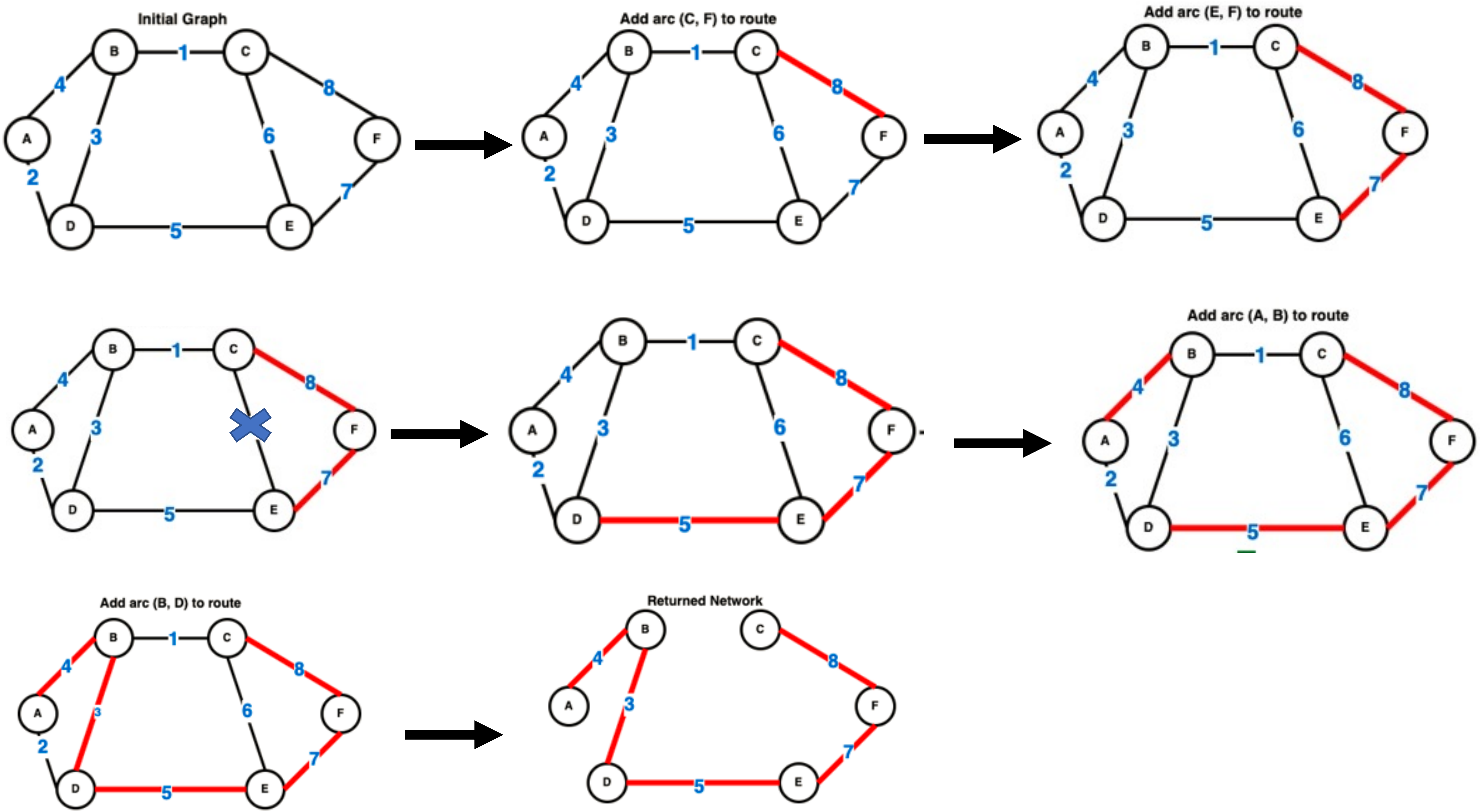
- Since the solution of the dynamic optimization procedure described previously, gives an estimate of the lower bound on the total egress time.
- Proposal of a path generating procedure is paramount to aid stakeholders plan accordingly.

Algorithm 1: Greedy Heuristic for Evacuation Route Planning

Input: Dynamic network $G_T = (N_T, A_T)$, with the set of source and sink nodes, $S \subset V$ and $0 \subset V$ respectively and DT = book-keeping (using time-series dictionary) of all the network dynamics obtained after the implementation of the dynamic optimization model in sections 4.3.1 and 4.3.2.

Output: Evacuation route plans for all evacuees.

```
Count the number w_ij of occurrences of (i, j) in DT.
Generate a weighted static graph G = (N, A, w) where w gives the arc frequencies
  calculated above.
Sort the arcs in G' from the highest to the lowest frequency.
Initialize T_r := (N, E) with E = ∅ (empty forest)
while (T_r is not yet connected) do
    Take an arc (i, j) with the largest frequency w_ij and check whether it forms or not a
      cycle with some arcs in E
    If not, E := E ∪ {(i, j)}.
Return a spanning tree T_r of maximum weight.
Re-run the dynamic optimisation model of Sections 4.3.1 and 4.3.2 on T_r.
```



Initial Graph
Add arc (C, F) to route
Add arc (E, F) to route
Add arc (A, B) to route
Add arc (B, D) to route
Returned Network

Complexity Analysis:

- Given a graph $G = (N, A)$: $|N| = n$ and $|A| = m$. The time complexity is computed as:

O($Tmlogm$)

O($mlogn$)

O($mlogm$)

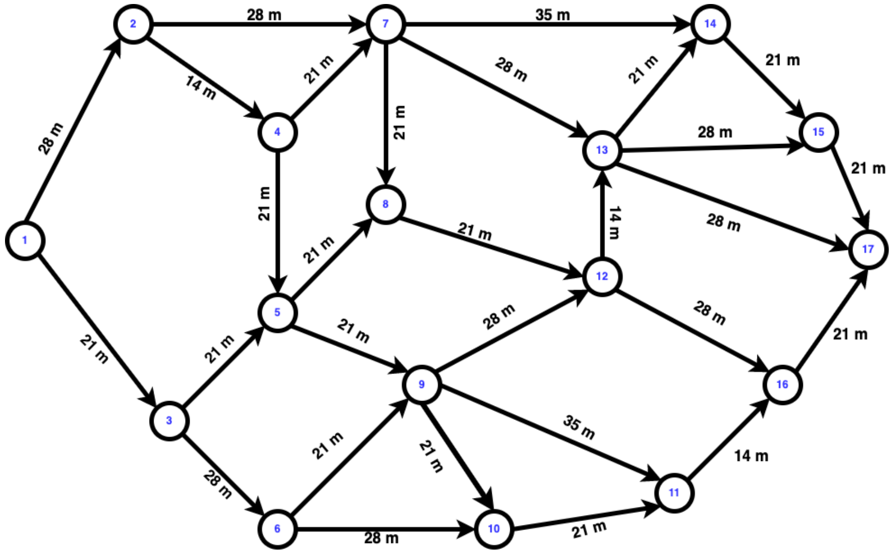
O(1)

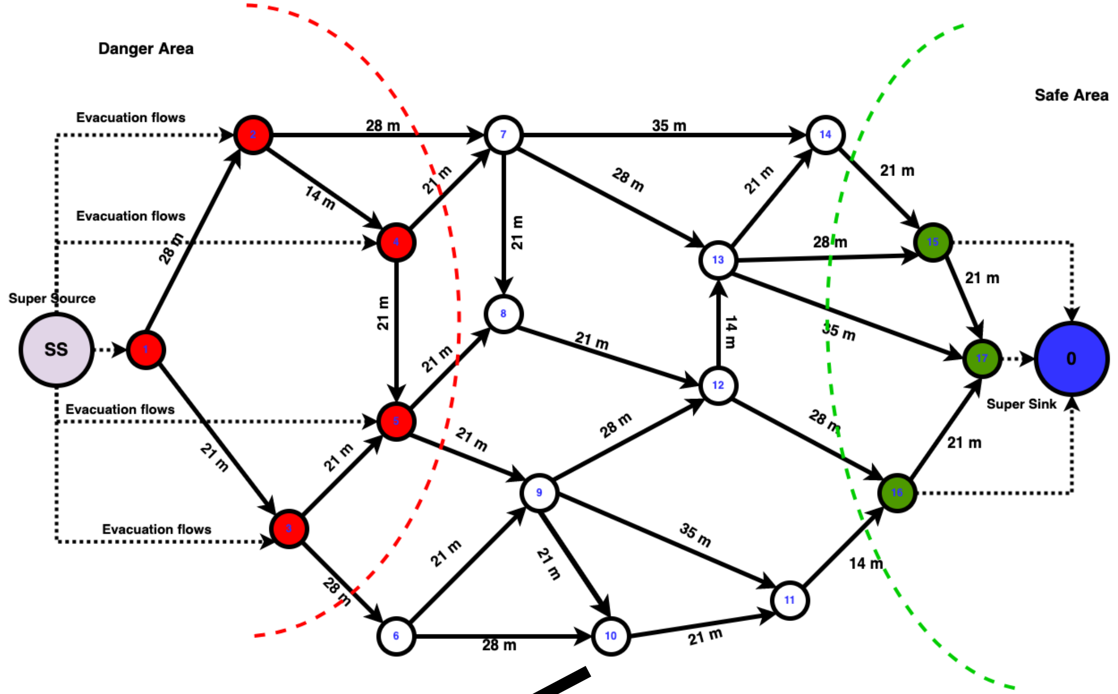
O($mlogm$)

Count the number w_{ij} of occurrences of (i, j) in DT.
Generate a weighted static graph $G = (N, A, w)$ where w gives the arc frequencies calculated above.
Sort the arcs in G' from the highest to the lowest frequency.
Initialize $T_r := (N, E)$ with $E = \emptyset$ (empty forest)
while *(T_r is not yet connected)* **do**
    Take an arc (i, j) with the largest frequency w_{ij} and check whether it forms or not a cycle with some arcs in E
    If not, $E := E \cup \{(i, j)\}$.
Return a spanning tree T_r of maximum weight.
Re-run the dynamic optimisation model of Sections 4.3.1 and 4.3.2 on T_r.

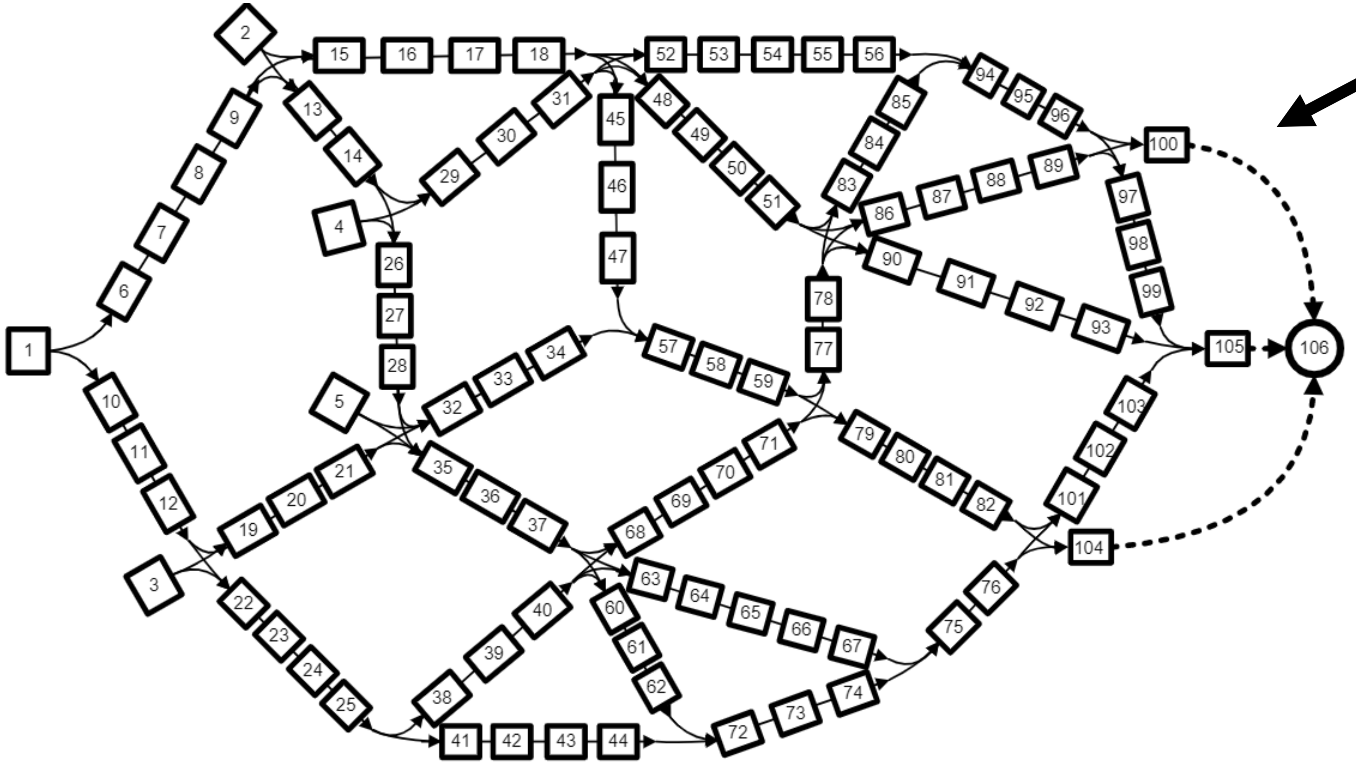
- Time Complexity: $\boldsymbol{O(Tmlogm + mlogn + mlogm + 1 + mlogm)}$
- Max arcs for complete graph: $\frac{n(n-1)}{2} \Rightarrow O(n^2)$
- Min arcs for connected graph: $n - 1 \Rightarrow O(n)$
- Worse case: $O(Tmlogm)$
- Best case: $O(Tmlogn)$

Sample Example





$\theta = 7 seconds$



Results

Base Network	Total Network clearance time (T)	Total egress time
DyCTEP	35	11422 (3 hr 10 min 22secs)
DyCTEP - Congestion	52	14473 (4 hr 1 min 12secs)
ORAA	54	14605 (4 hr 3 min 25 secs)
Shortest Path	72	19859 (5 hr 31 min)

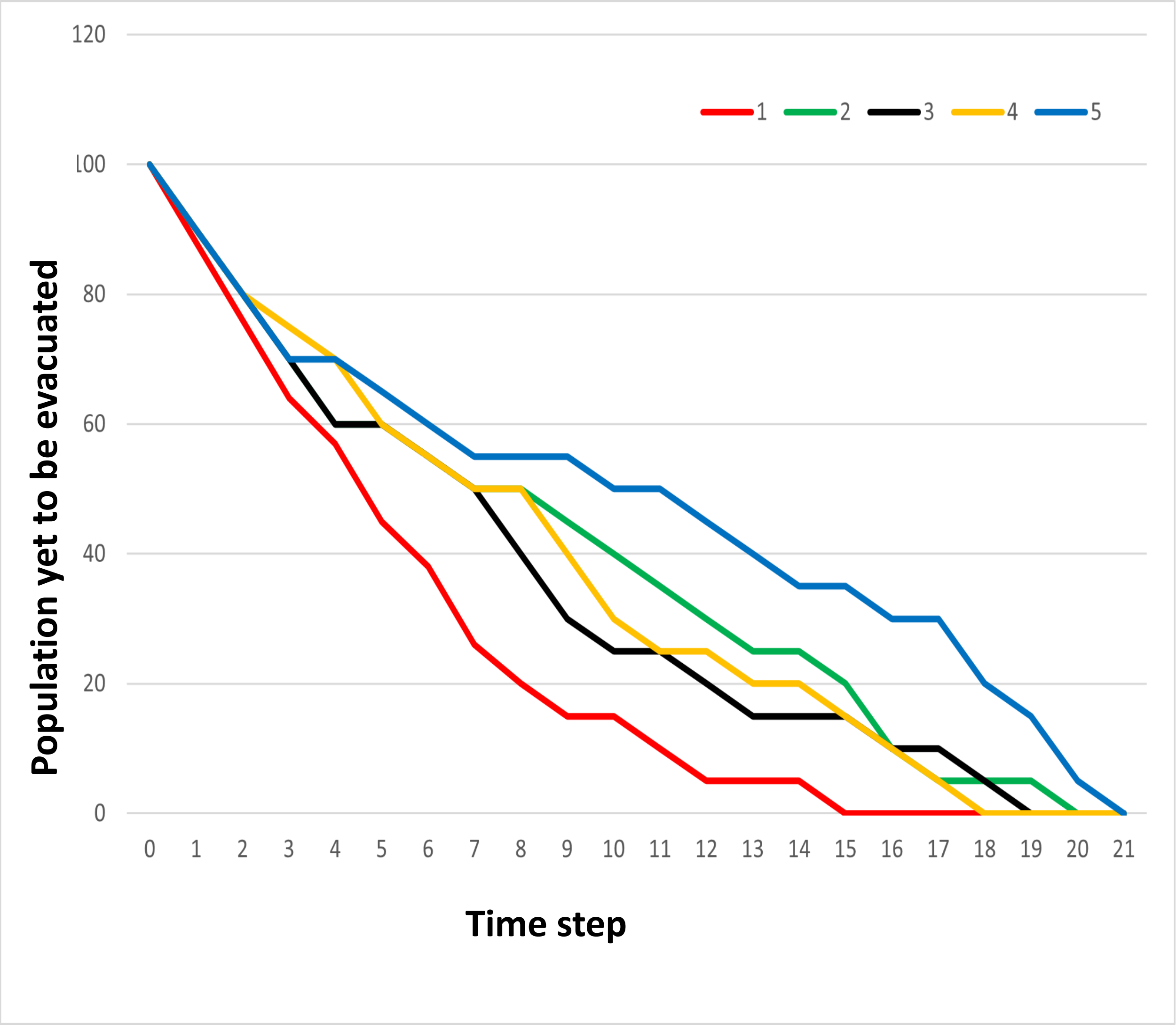
Optimal distribution of flow units for source cell connectors

Time-step	Connectors / Arc									
	(1, 6)	(1, 10)	(2, 15)	(2, 13)	(3, 19)	(3, 22)	(4, 26)	(4, 29)	(5, 32)	(5, 35)
0	0	0	0	0	0	0	0	0	0	0
1	7	5	5	5	5	5	5	5	5	5
2	7	5	5	5	5	5	5	5	5	5
3	7	5	5	5	5	5	5	0	5	5
4	7	0	5	5	5	5	5	0	0	0
5	7	5	0	0	0	0	5	5	5	0
6	7	0	0	5	0	5	5	0	0	5
7	7	5	0	5	5	0	5	0	0	5
8	1	5	0	0	5	5	0	0	0	0
9	0	5	5	0	5	5	5	5	0	0
10	0	0	0	5	5	0	5	5	0	5
11	0	5	5	0	0	0	5	0	0	0
12	0	5	5	0	0	5	0	0	0	5
13	0	0	5	0	0	5	0	5	0	5
14	0	0	0	0	0	0	0	0	0	5
15	5	0	5	0	0	0	0	5	0	0
16	0	0	5	5	0	5	5	0	0	5
17	0	0	5	0	0	0	0	5	0	0
18	0	0	0	0	0	5	0	5	5	5
19	0	0	0	0	0	5	0	0	0	5
20	0	0	5	0	0	0	0	0	5	5
21	0	0	0	0	0	0	0	0	0	0

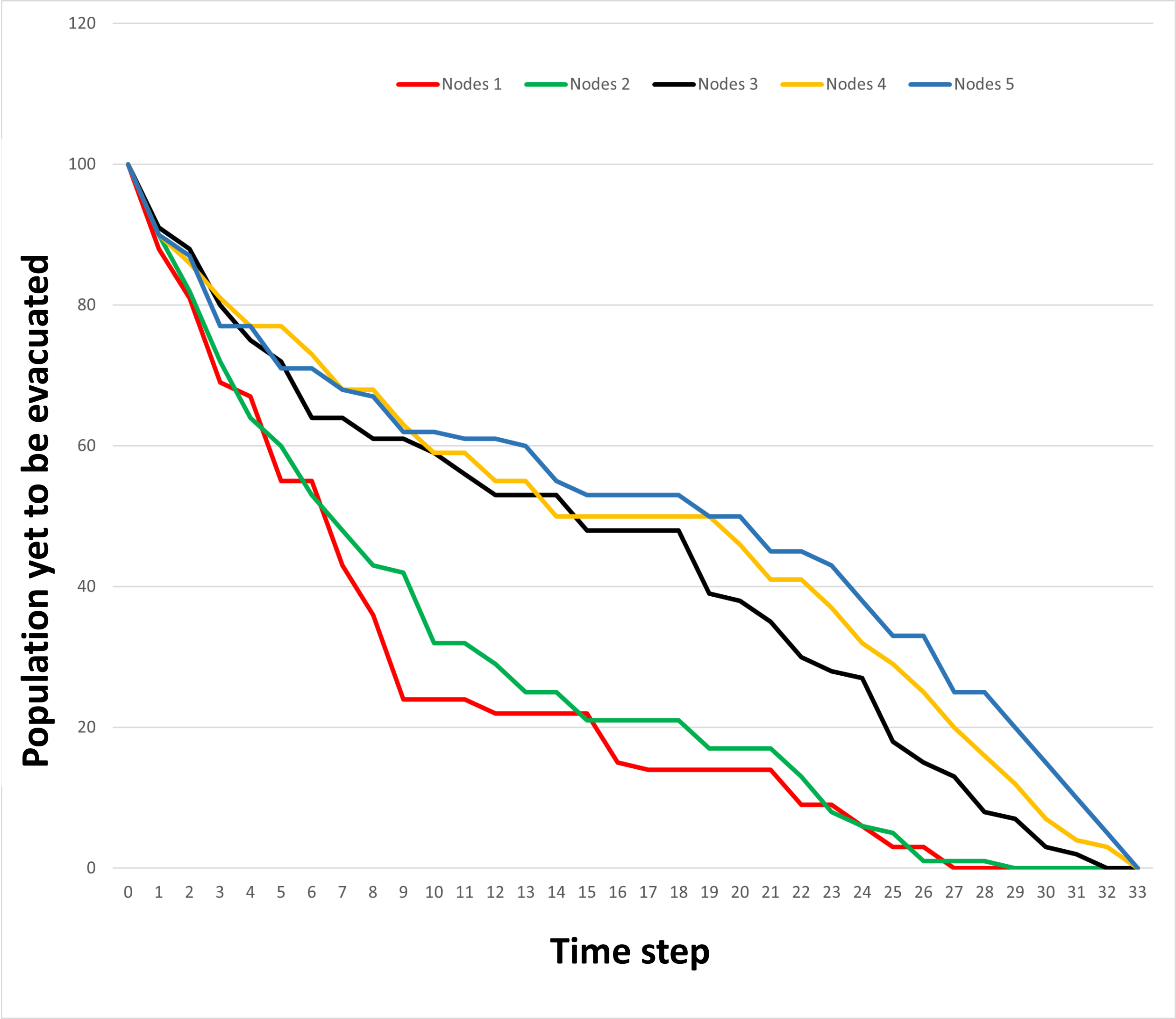
Optimal staging of flow units at source cells - DyCTEP

	Time (T)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Node	1	100	88	76	64	57	45	38	26	20	15	15	10	5	5	5	0	0	0	0	0	0
	2	100	90	80	70	60	60	55	50	50	45	40	35	30	25	25	20	10	5	5	5	0
	3	100	90	80	70	60	60	55	50	40	30	25	25	20	15	15	15	10	10	5	0	0
	4	100	90	80	75	70	60	55	50	50	40	30	25	25	20	20	15	10	5	0	0	0
	5	100	90	80	70	70	65	60	55	55	55	50	50	45	40	35	35	30	30	20	15	5

Optimal stagging at origin for DyCTEM vs DyCTEM-Congestion

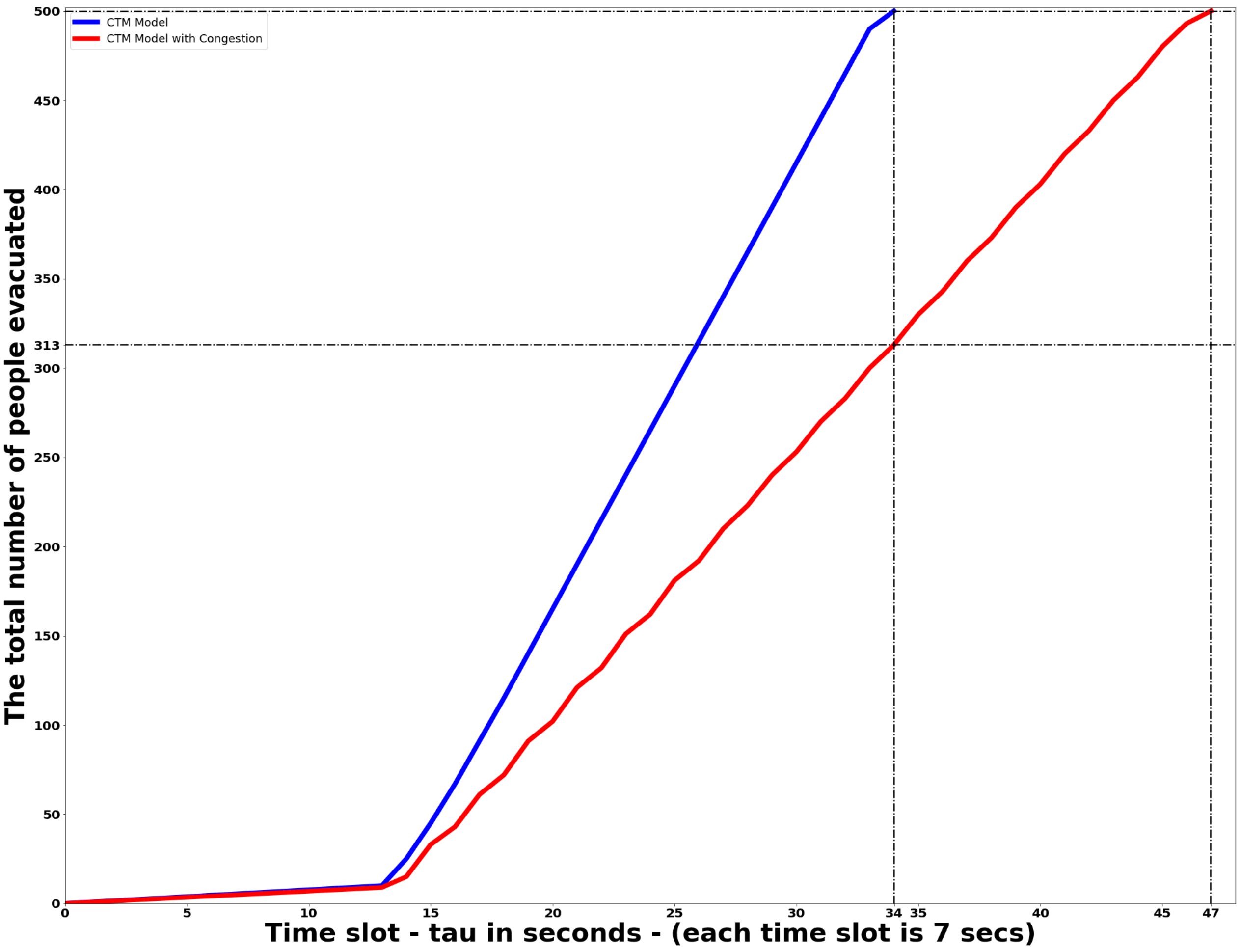


Optimal stagging and flow distributions at the source cells for each time slot τ for base model

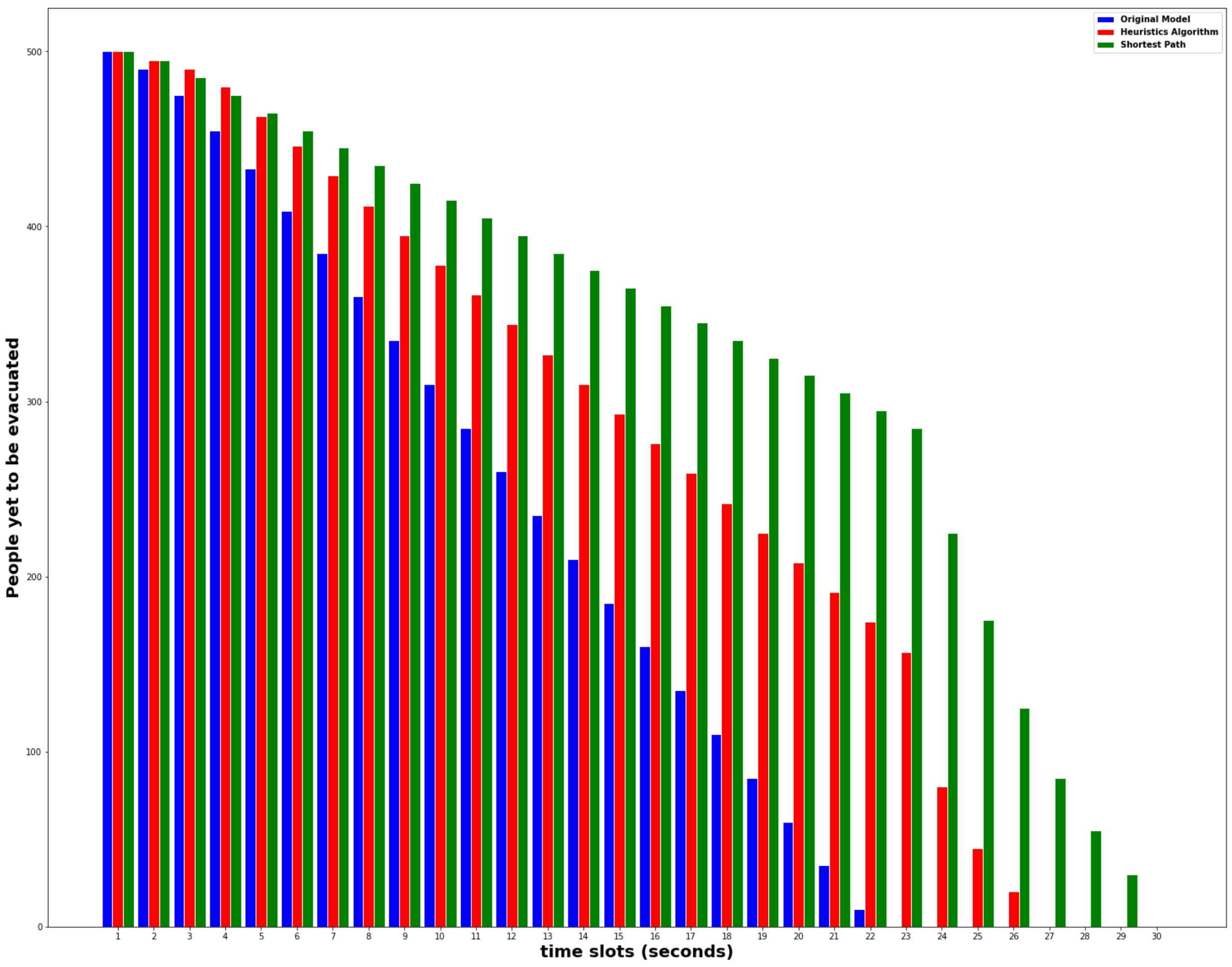


Optimal stagging and flow distributions at the source cells for each time slot τ for model with arc-congestion

Comparison of the model performance

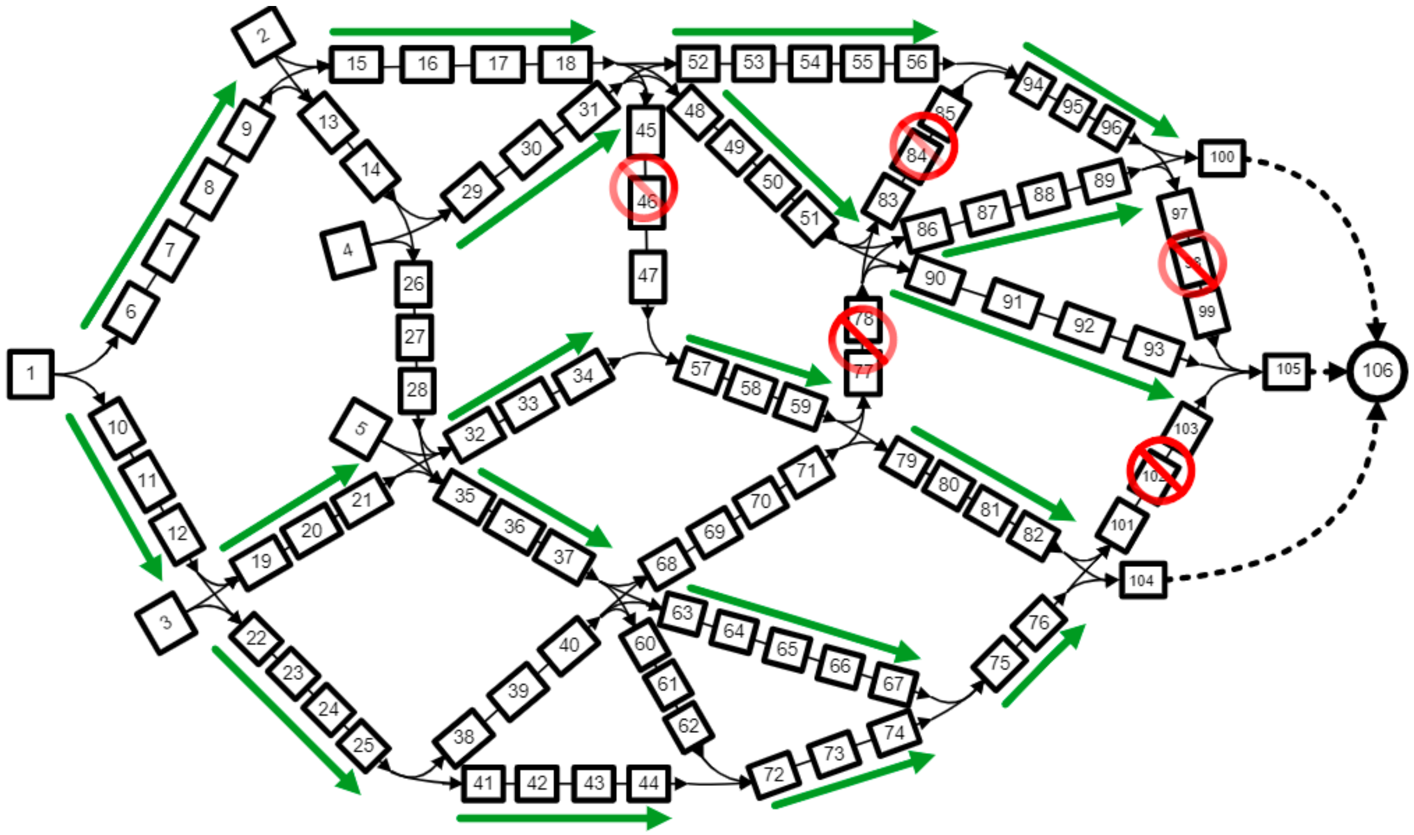


Number of people safely evacuated in DyCTEM vs DyCTEM-Congestion at every time slot τ



Comparison of the model performance on the various networks (the original network, the network generated by the heuristics and the shortest path network)

Optimal Routes generated by ORAA



Optimal route assignment by Heuristic Algorithm

Optimal destinations:

- The optimal distribution of flows at the destinations are as follows:
- Destination 15 (cell 100) received 135 flow-units (25% of the total demand).
- Destination 16 (cell 104) received 285 flow-units (57% of the total demand).
- Destination 17 (cell 105) received 80 flow-units (16% of the total demand).

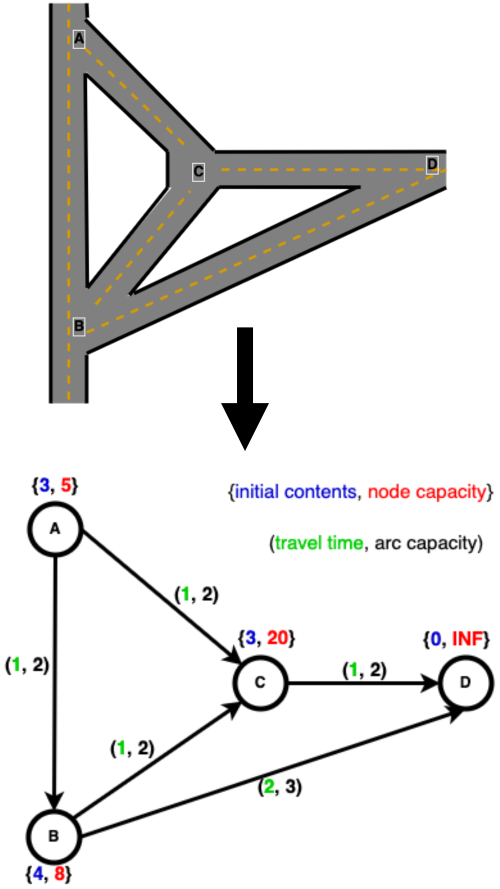
Alternative Formulations

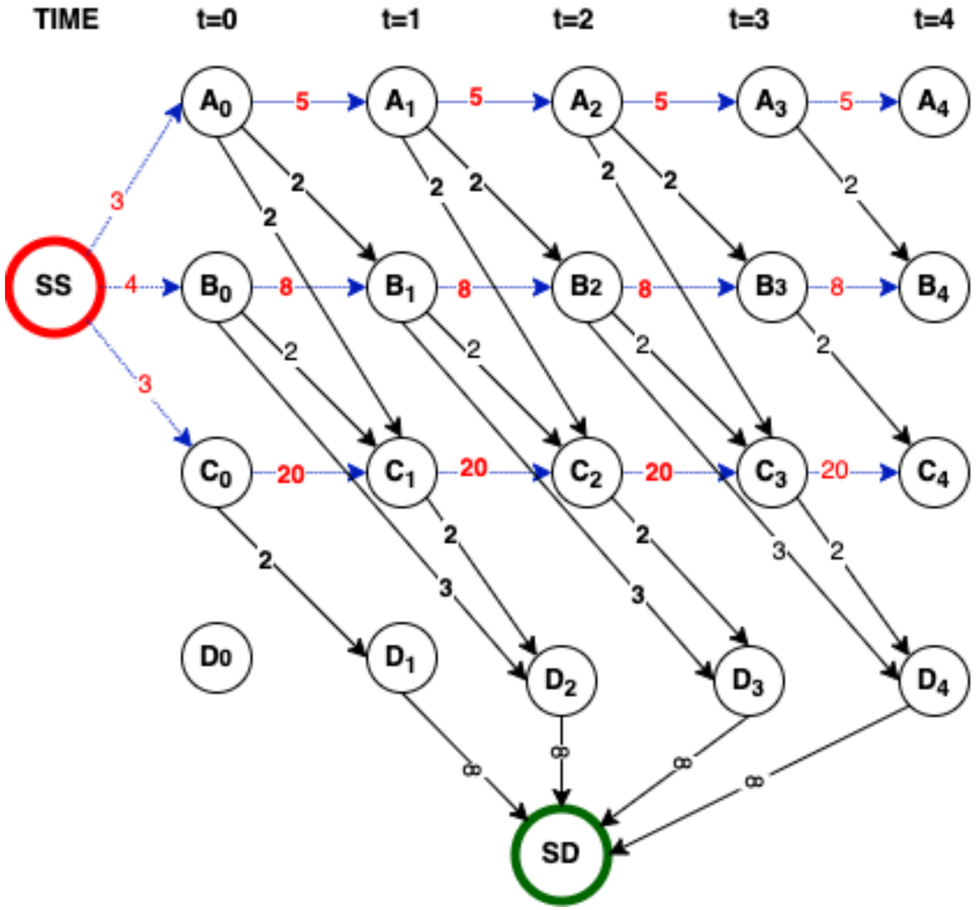
- The DyCTEP discussed has a major weakness.
- The use of cells with fixed single size may lead to a too large number of cells, unnecessary to meet the required level of network and operation accuracy.
- So many cells imply an excessive number of constraints and variables in the optimization model, which may turn out to be unpractical for real use.
- Three different approaches are proposed to cope with this inconvenience.
- Dynamic Earliest Arrival Flow (DEAF)
- Extended CTM
- Multiple Cell-Sizes

Dynamic Earliest Arrival Flow (DEAF)

❖ Given a network $G = (N, A)$, let $G_T = (N_T, A_T)$ be the TEG over horizon T, where $N_T \coloneqq \{i^t \mid i \in N; t \in T\}$ and

$A_T = A_M \cup A_H$ such that $A_M \coloneqq \{(i^t, j^{t'}) \mid (i,j) \in A; t' = t + \lambda_{ij},\ t \in T\}$ and $A_H \coloneqq \{(i^t, i^{t+1}) \mid i \in V; t = 0,1,\ldots,T-1\}$





❖ **Proposition:** If $n \coloneqq |N|$ and $m \coloneqq |A|$ then $n(T+1)$ and $(n+m)T + m - \sum_{(i,j)\in A} \lambda_{ij}$ are the upper bounds for the number of nodes and arcs in G_T without the super-source and super-sink nodes, respectively

Parameters and formulation:

- **Additional Parameters:**
  - $\lambda_{ij} = \lambda_{ji}$ **: The travel time, i.e the time needed to travel from node i to node j.**
  - q_i: **The initial occupancy of cell i**
  - z_i^{t+1}: **Flows from node i at time *t* to the same node with travel time** $\lambda_{ii} = 1$

$$\text{Problem (EAF): } \min \sum_{t=1}^{T} \sum_{i \in D} x_{i0}^t \tag{5.1a}$$

$$z_i^{t+1} - z_i^t - \sum_{j:ji \in A} x_{ji}^{t-\lambda_{ji}} + \sum_{j:ij \in A} x_{ij}^t = 0, \quad \forall i \in V \setminus \{S \cup 0\}; t = 0, 1, \cdots, T \tag{5.1b}$$

$$z_0^{t+1} - z_0^t - \sum_{j:j0 \in D} x_{j0}^t = 0, \quad \forall t = 0, \cdots, T \tag{5.1c}$$

$$\sum_{t=0}^{T} \sum_{i \in D} x_{i0}^t = \sum_{j \in S} q_j \tag{5.1d}$$

$$\sum_{j:ji \in A} x_{ji}^t + z_i^t \le n_i, \quad \forall i \in V \setminus \{0\}, t \in T \tag{5.1e}$$

$$0 \le x_{ij}^t \le c_{ij}, \quad \forall (ij) \in A, t = \{0, 1, \cdots, T - \lambda_{ij}\} \tag{5.1f}$$

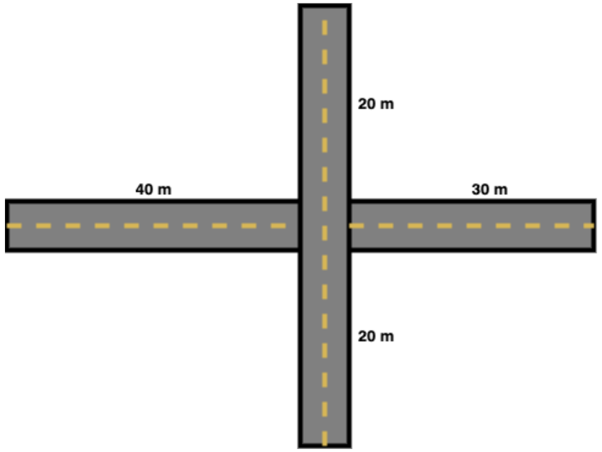
$$x_{si}^0 = q_i, \quad \forall i \in S \tag{5.1g}$$

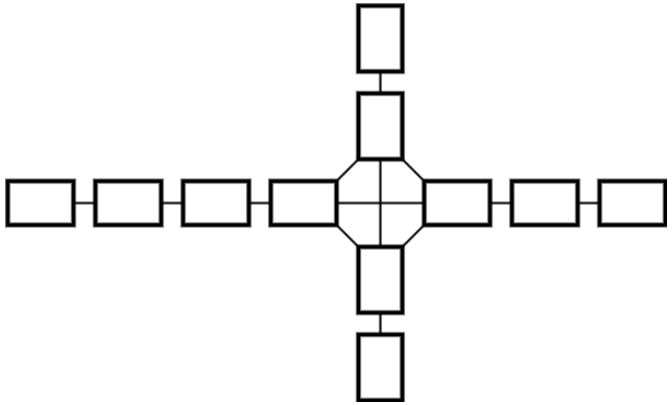
$$z_i^0 = 0, \quad \forall i \in V \tag{5.1h}$$

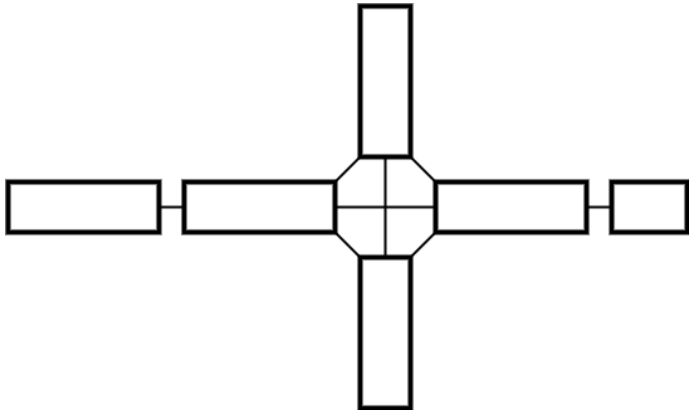
$$z_i^t = 0, \quad \forall i \in D, \forall t \in T \tag{5.1i}$$

Multiple cell sizes approach

- To represent a given network with the CTM, it is necessary to choose a cell size that adequately matches the length of the network arcs.
- As one easily understand, this leads to a trade-off between the cell number (which greatly affects the number of side constraints and variables) and the accuracy of the network representation.







- The DyCTEP is then extended using of multiple cell sizes, with larger cell sizes being integer multiples of a reference unit size (this is necessary to comply with the discrete nature of the DyCTEP approach).

Extended CTM: Approach 1

- The basic idea of this approach is to divide a cell into subcells, where the number of subcells corresponds to the cell size of the cell $(1, \dots, n)$.
- A pedestrian needs at least one period to pass a subcell so that *n* subcells lead to a minimum travel time of *n* periods.
- The DyCTEP with multiple cell sizes using this approach can be formulated by replacing Eqns 1.10b by 3.2a, and 1.10d by 3.2b and adding 4 more constraints (3.2c - 3.2f)

- $$y_i^t - y_i^{t-1} - \sum_{j:ji \in A} x_{ji}^{t-1} + \sum_{j:ij \in A} x_{ij}^{t-1} = 0; \forall i \in C_1, t \in \mathrm{T}, t > 0 \qquad (\mathbf{3.2a})$$
- $$y_i^t - y_i^{t-1} + \sum_{j:ij \in A} x_{ij}^{t-1} + \sum_{k \in K} x_{i(k,k+1)}^{t-1} = \begin{cases} q_i; \ t = 1 \\ 0; \forall t > 1 \end{cases}; \forall i \in S \qquad (\mathbf{3.2b})$$
- $$y_i^t - y_i^{t-1} - \sum_{j:ji \in A} x_{ji}^{t-1} + \sum_{j:ij \in A} x_{ij}^{t-1} - \sum_{k=1}^{n-1} x_{i(k,k+1)}^t + \sum_{k=1}^{n-1} x_{i(k,k+1)}^{t-1} = 0; n \in K: n \geq 2; i \in C_n; \ t = \{2, \dots, T\} \qquad (\mathbf{3.2c})$$
- $$x_{i(k+1,k+2)}^t = x_{i(k,k+1)}^{t-1}; n \in K: n \geq 3; k = 1,2, \dots, n-2; i \in C_n; t = \{2, \dots, T\} \qquad (\mathbf{3.2d})$$
- $$\sum_{j:ij \in A} x_{ij}^t = x_{i(k-1,k)}^{t-1}; \mathrm{k} \in K: k \geq 2; i \in C_n; t = \{2, \dots, T\} \qquad (\mathbf{3.2e})$$
- $$x_{i(k,k+1)}^t \geq 0; k \in K \ ; i \in V, t \in T \qquad (\mathbf{3.2f})$$

Problem: SO-DTA (CTM) : $\min \sum_{t \in \mathfrak{T}} \sum_{i \in V \setminus 0} y_i^t$ (1.10a)

$$y_i^t - y_i^{t-1} - \sum_{j:ji \in A} x_{ji}^{t-1} + \sum_{j:ij \in A} x_{ij}^{t-1} = 0, \quad \forall i \in V \setminus \{S \cup 0\}, t \in T, t > 0 \qquad (1.10b)$$

$$y_0^t - y_0^{t-1} - \sum_{j:j0 \in A} x_{j0}^{t-1} = 0, \quad t \in T, t > 0 \qquad (1.10c)$$

$$y_i^t - y_i^{t-1} + \sum_{j:ij \in A} x_{ij}^{t-1} = \begin{cases} q_i, & \text{for } t = 1 \\ 0, & \text{for } \forall t > 1 \end{cases}, \quad \forall i \in S \qquad (1.10d)$$

$$\sum_{j:ji \in A} x_{ji}^t \leq Q_i, \quad \forall i \in V \setminus \{S\}, t \in T \qquad (1.10e)$$

$$\sum_{j:ji \in A} x_{ji}^t \leq \delta_i (n_i - y_i^t), \quad \forall i \in V \setminus \{S\}, t \in T \qquad (1.10f)$$

$$\sum_{j:ij \in A} x_{ij}^t \leq Q_i, \quad \forall i \in V \setminus \{0\}, t \in T \qquad (1.10g)$$

$$\sum_{j:ij \in A} x_{ij}^t - y_i^t \leq 0, \quad \forall i \in V \setminus \{0\}, t \in T \qquad (1.10h)$$

$$0 \leq x_{ij}^t + x_{ji}^t \leq c_{ij}, \quad \forall (ij) \in A, t \in T \qquad (1.10i)$$

$$y_i^0 = 0, \quad \forall i \in V \qquad (1.10j)$$

$$x_{ij}^0 = 0, \quad \forall (i,j) \in A \qquad (1.10k)$$

Multiple Cell Sizes – Approach 2

- The concept of the second approach to capture multiple cell sizes is to limit traffic outflow with respect to traffic inflow of a cell so that a minimum travel time of *n* periods for a cell of size *n* can be ensured.

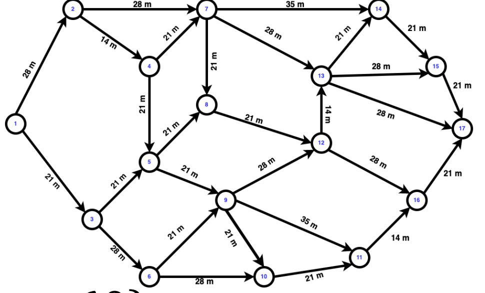
- Because of constraint *1.10b* this assumption automatically holds for cells with size 1.

- For cells of size $k \geq 2$, we introduce constraint *3.3a* to ensure a minimum travel time of k_i periods for a cell ***i*** of size k_i.

- The DyCTEP with multiple cell sizes using the 2nd approach can be formulated by adding the following constraint to the model formulation *1.10b - 1.10k*.

- $\sum_{j:ij\in A} \sum_{\tau=0}^{t} x_{ij}^{\tau} \leq \sum_{j:ji\in A} \sum_{\tau=1}^{\max(t-k_i,1)} x_{ji}^{\tau} + \sum_{\tau=1}^{\max\left(t-{}^{k_i}/_2+1,1\right)} y_i^{\tau} \; ; i \in V: k_i \geq 2; t = \{2, \ldots, T\}$ **(3.3a)**

Experimentation and Results



- Using the sample network from the previous example:
- Analysis of the various formulations was carried
- The unit time slot of $\theta = 7\ secs$ was assumed and the analysis was performed for $\tau = \{1, \ldots, 60\}$

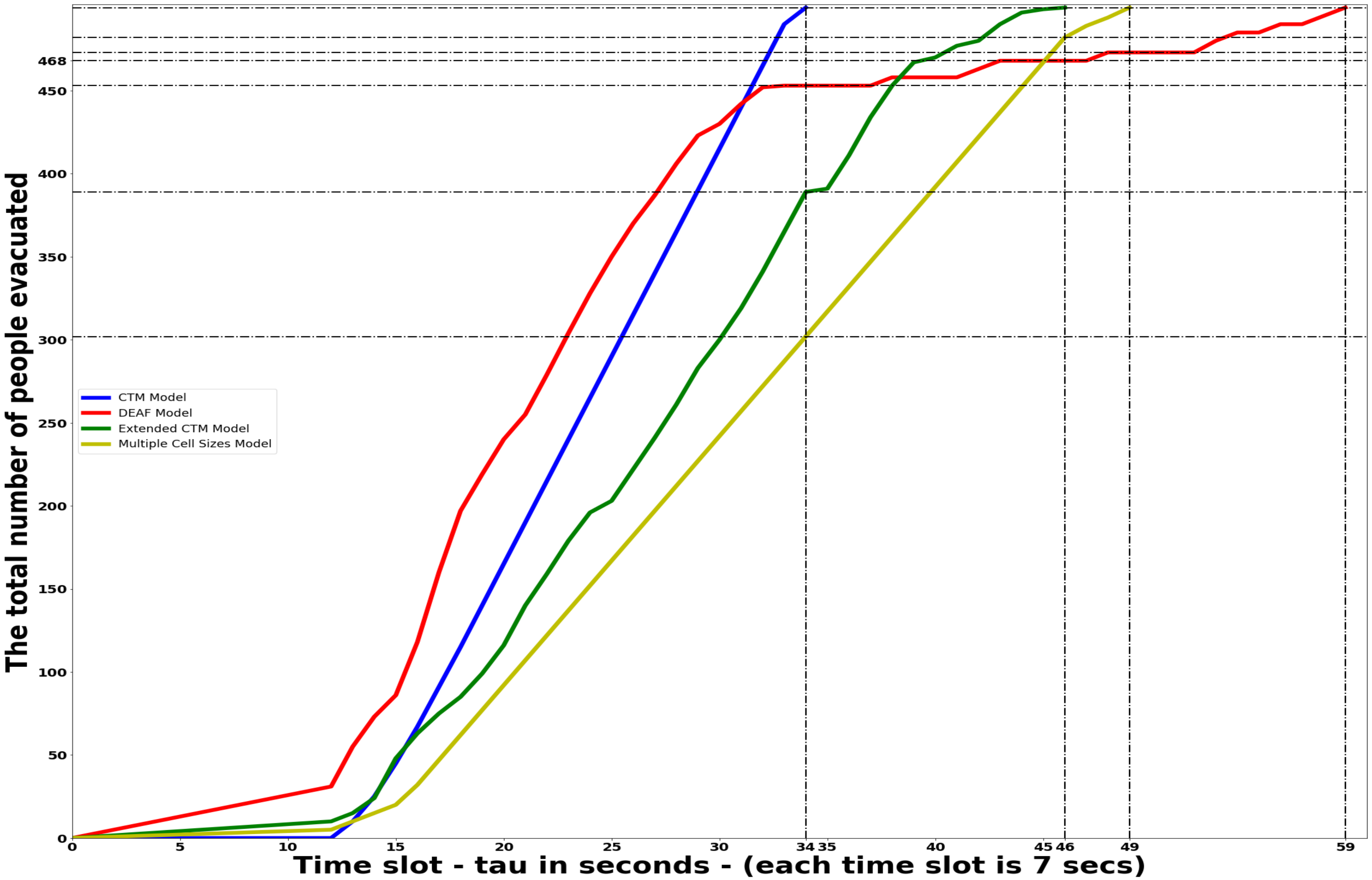
Model size comparison

Model	# Variables	# Constraints
DyCTEP	14760	39474
DEAF	3416 (-76.9%)	8667 (-78.0%)
APPROACH 1	6776 (-54.1%)	12206 (-69.1%)
APPROACH 2	5700 (-61.4%)	10954 (-72.3%)
CONGESTION		
DyCTEP	59040 (+300%)	70175 (+77.8%)
DEAF	13440 (-8.9%)	22913 (-42.0%)
APPROACH 1	18278 (+23.8%)	24758 (-37.3%)
APPROACH 2	22800 (+54.5%)	26820 (-32.1%)

Comparison of performance

Model	Network Clearance Time (Time steps)	Total Egress Time
DyCTEP	34	11422 (3 hr 10 min 22 secs)
DEAF	59	14473 (4 hr 1 min 13 secs)
APPROACH 1	46	13354 (3 hr 42 min 34 secs)
APPROACH 2	49	14006 (3 hr 53 min 26 secs)
CONGESTION		
DyCTEP	53	14605 (4 hr 3 min 25 secs)
DEAF	94	33060 (9 hr 11 min 1 secs)
APPROACH 1	64	17896 (4 hr 58 min 16 secs)
APPROACH 2	69	18971 (5 hr 13 min 11 secs)

Results: Comparative analysis of egress times for different models



Real Life case application: L’Aquila

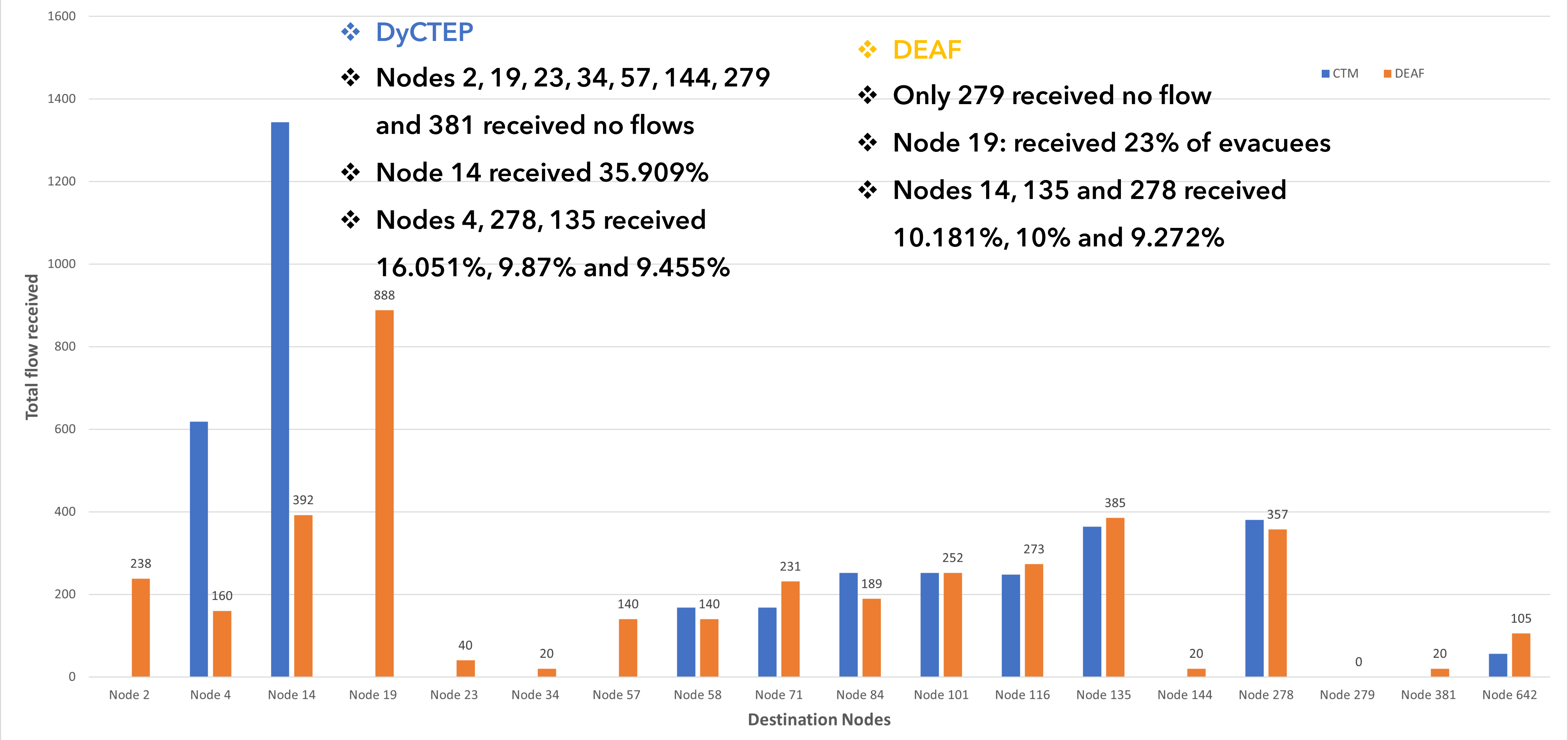
- For our case study, we considered Piazza del Duomo (L’Aquila) and took a 750m radii network along the streets
- Resulting in a network with total street length of 47353.602 meters.
- Using θ = 7 secs, the transformed cell network is composed of 6492 cells and 7772 connectors.
- A total of 77 source nodes chosen s.t deg(i) ≥ 3.
- Initial source occupancy = 50 evacuees each, making a total of N =3850 people to be safely evacuated from the danger zone to the safe locations
- Destination nodes consist of 18 nodes (nodes 2, 4, 14, 19, 23, 34, 57, 58, 71, 84, 101, 116, 135, 144, 278, 279, 381, and 642) connected to the virtual super-sink node 0.

Results

Model	Network Clearance Time (Time steps)	Total Egress Time (Time Units)
DyCTEP	173	127203 = 35 hours 20 minutes and 3 seconds
DEAF	205	144885 = 40 hours 14 minutes and 30 seconds

- An extra 5 hours needed to evacuate all the evacuees in DEAF as compared to DyCTEP

Comparison of Optimal destination flow distribution for models DyCTEP and DEAF

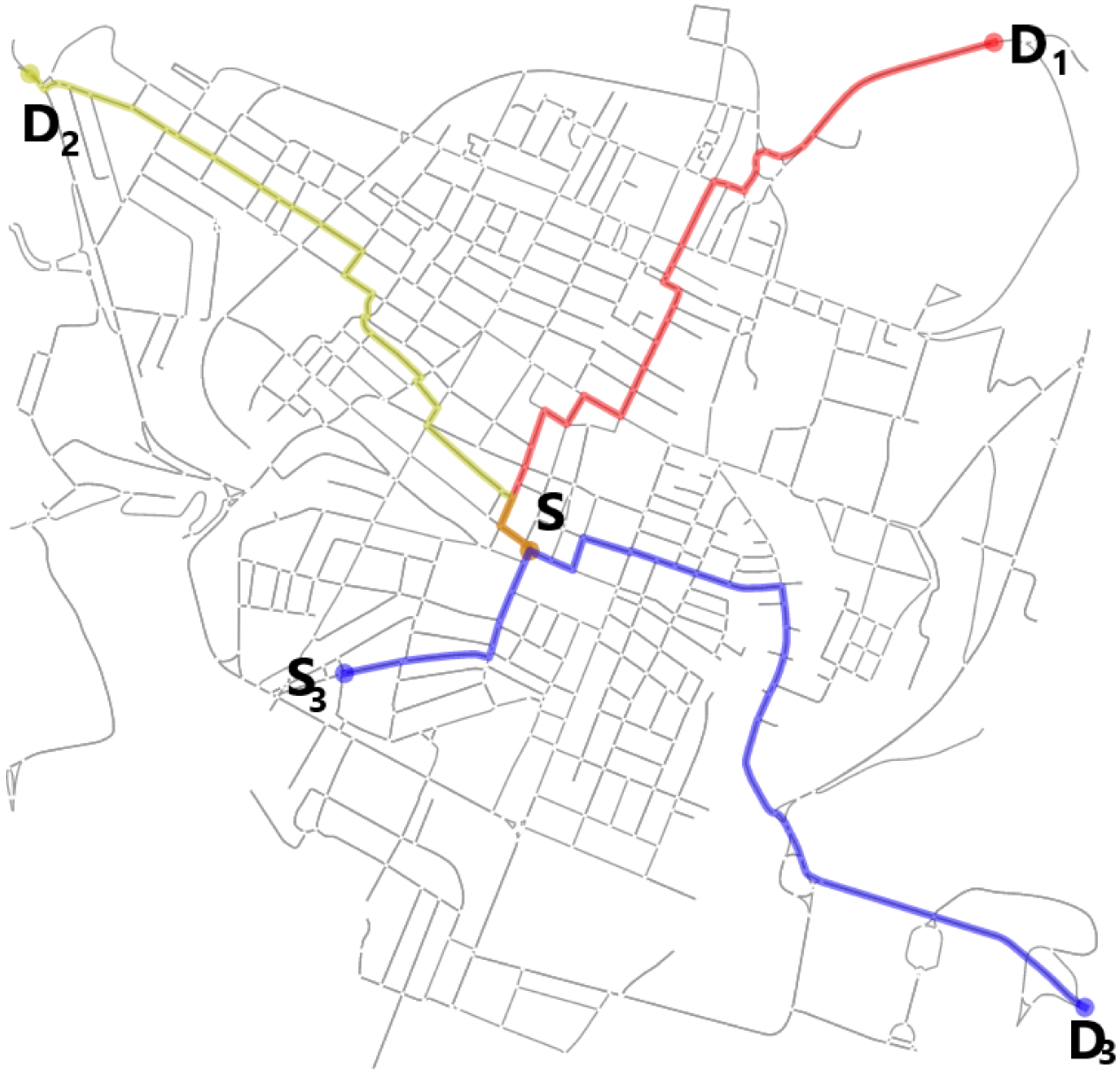


Routes generated by ORAA on DyCTEP solution

$|SD_1| = 1216\,m$

$|SD_2| = 1118\,m$

$|S_3D_3| = 1627\,m$

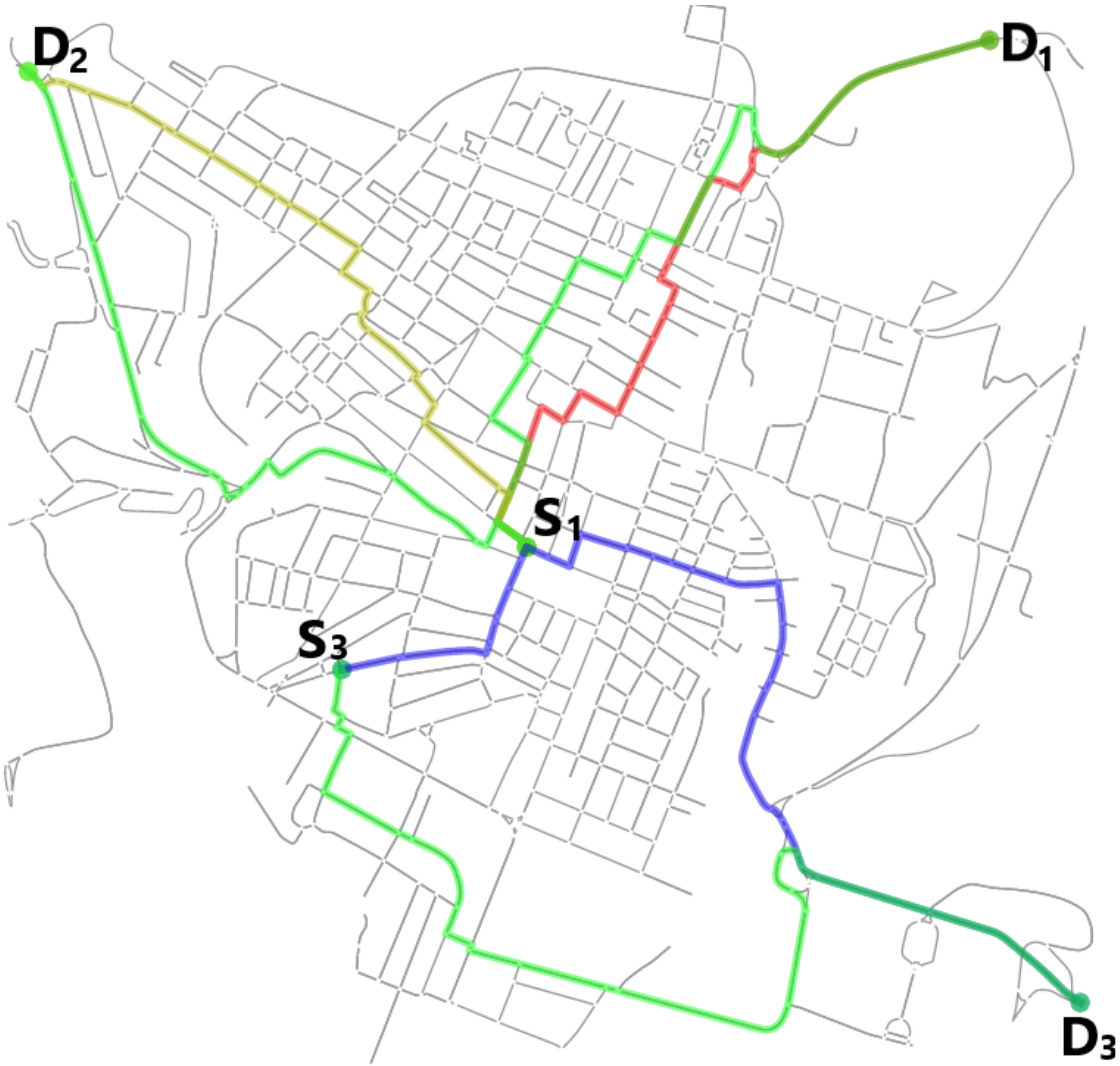


Routes assignment comparison betwen DyCTEP and DEAF (in green)

$|SD_1| = 1330\ m$

$|SD_2| = 1202\ m$

$|S_3D_3| = 1745\ m$

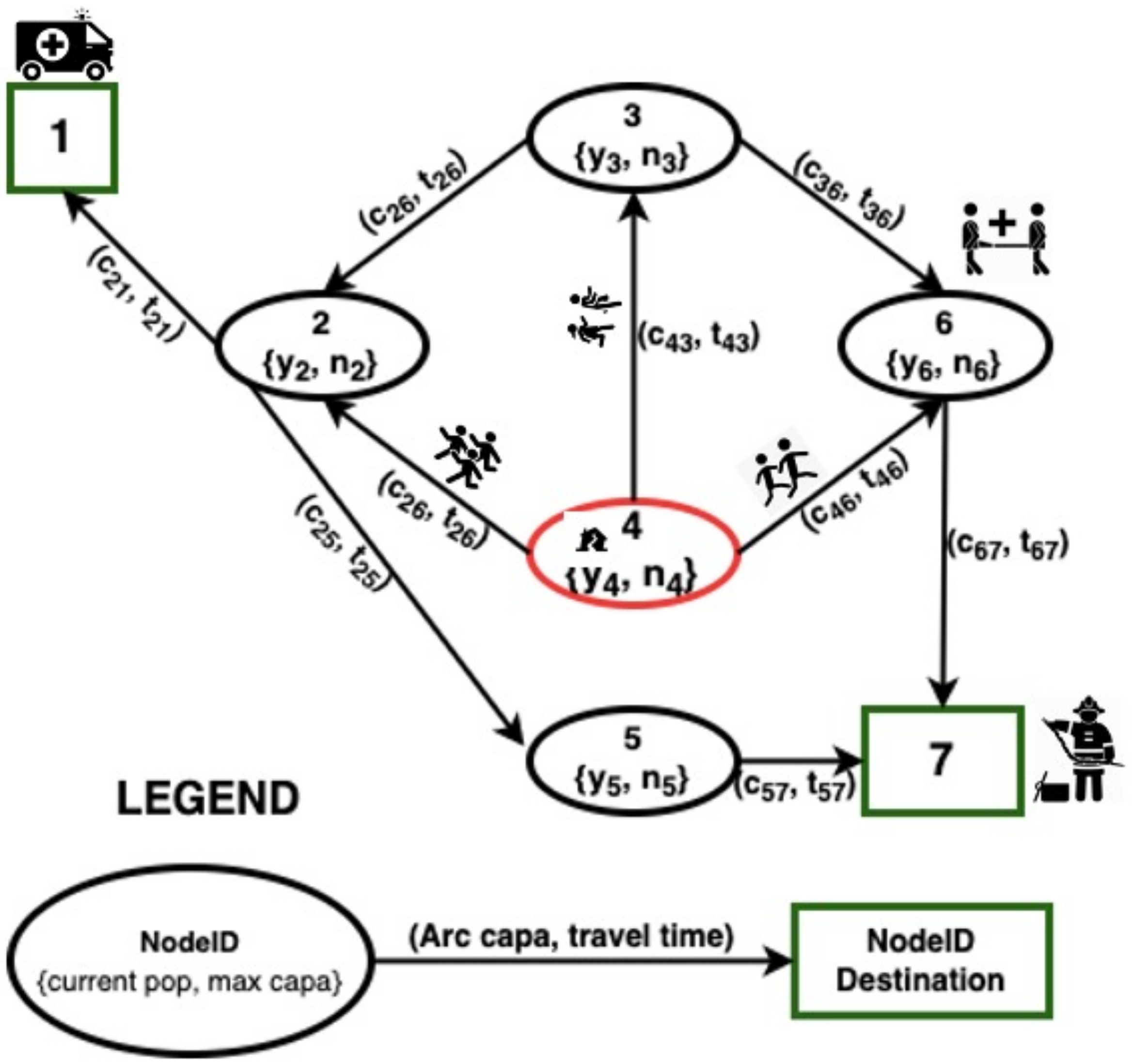


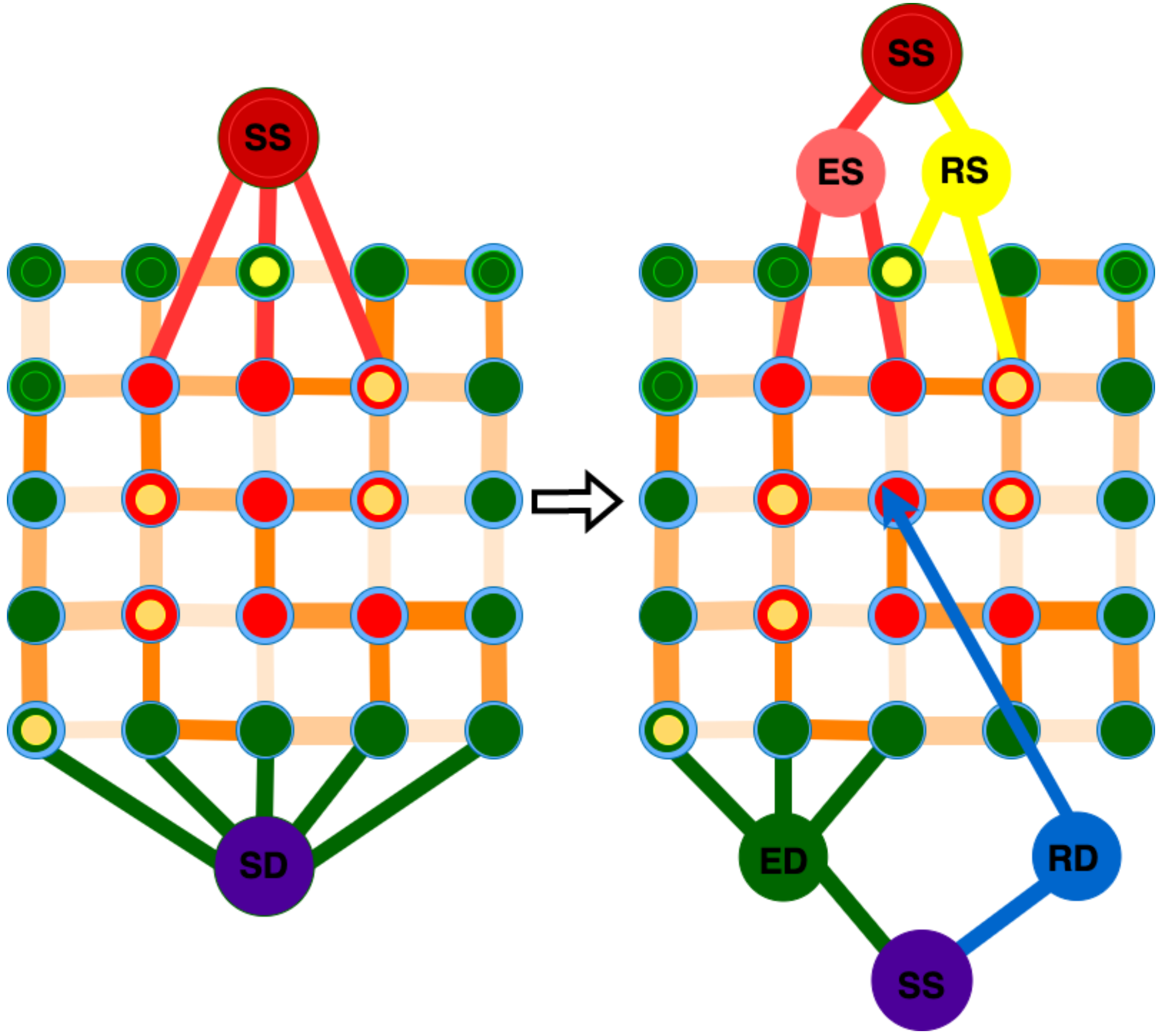
$|SD_1| = 1216\ m$

$|SD_2| = 1118\ m$

$|S_3D_3| = 1627\ m$

Priority Multi-Party Capacity Constrained Route Planning





Algorithm: PMP-CCRP

- **The Priority Multi-party Capacity Constrained Route Planning is an extension of the Capacity Constrained Route Planning (CCRP) of Shekhar et al.**

Algorithm 2: Priority Multi-Party Capacity Constraint Route Planning (PMP-CCRP)

Input: spatial network $G = (N, E)$, with the set of source and sink nodes, $S \subset N$ and $D \subset N$ respectively and book-keeping of available capacities of G using time-series dictionary

Output: Evacuation plan: Routes with schedules of evacuees on each path

Generate party specific pseudo sub-sources (E_s and R_s) and pseudo sub-sinks (E_D and R_D) connected to the respective source and sink nodes with 0 travel times and ∞ capacities.

Add super-source (S_S) and super-sink (D_S) connected by edges of 0 travel times and ∞ capacities to the respective sub-sources and sub-sinks.

Categorize each source node based on priority

while *(any source has evacuees)* **do**

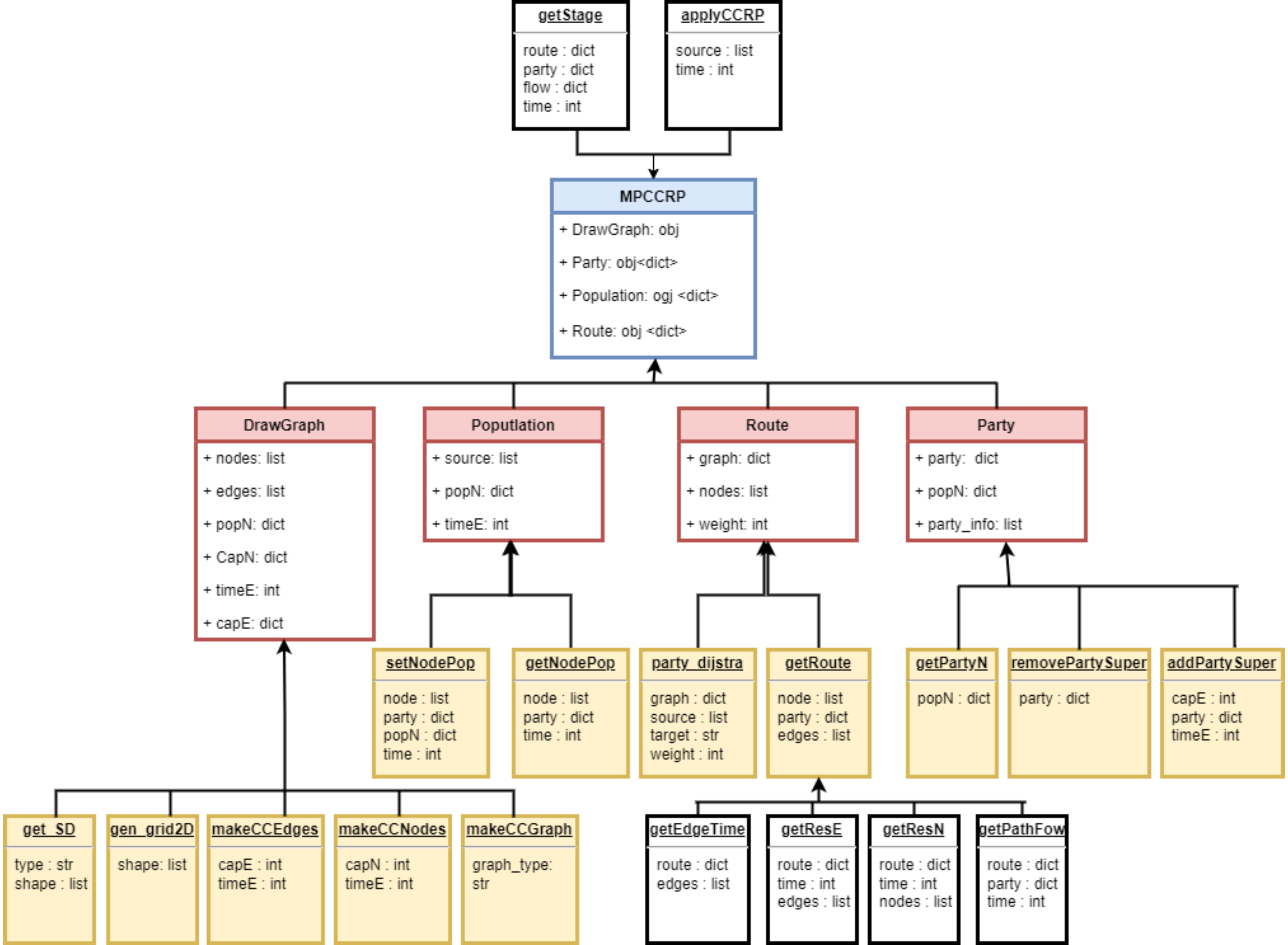
    Find the shortest path P between the two super nodes (S_S and D_S) using the generalized Dijkstra's algorithm with edge travel times and node priorities as the weight criteria

    Calculate the maximum flow x_{max} along this path P

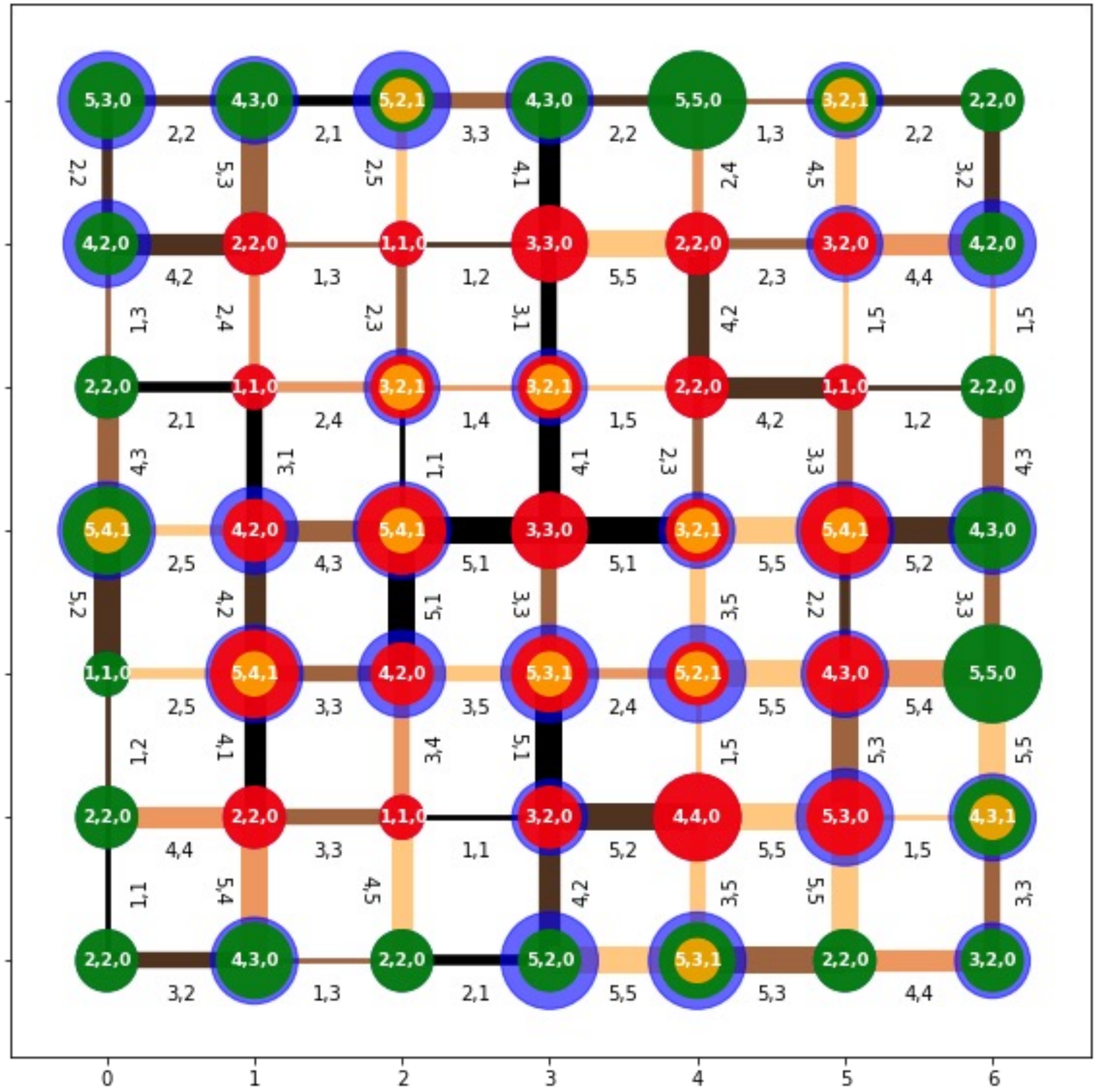
    Reserve the node and arc capacities

    Update the book keeping dictionary

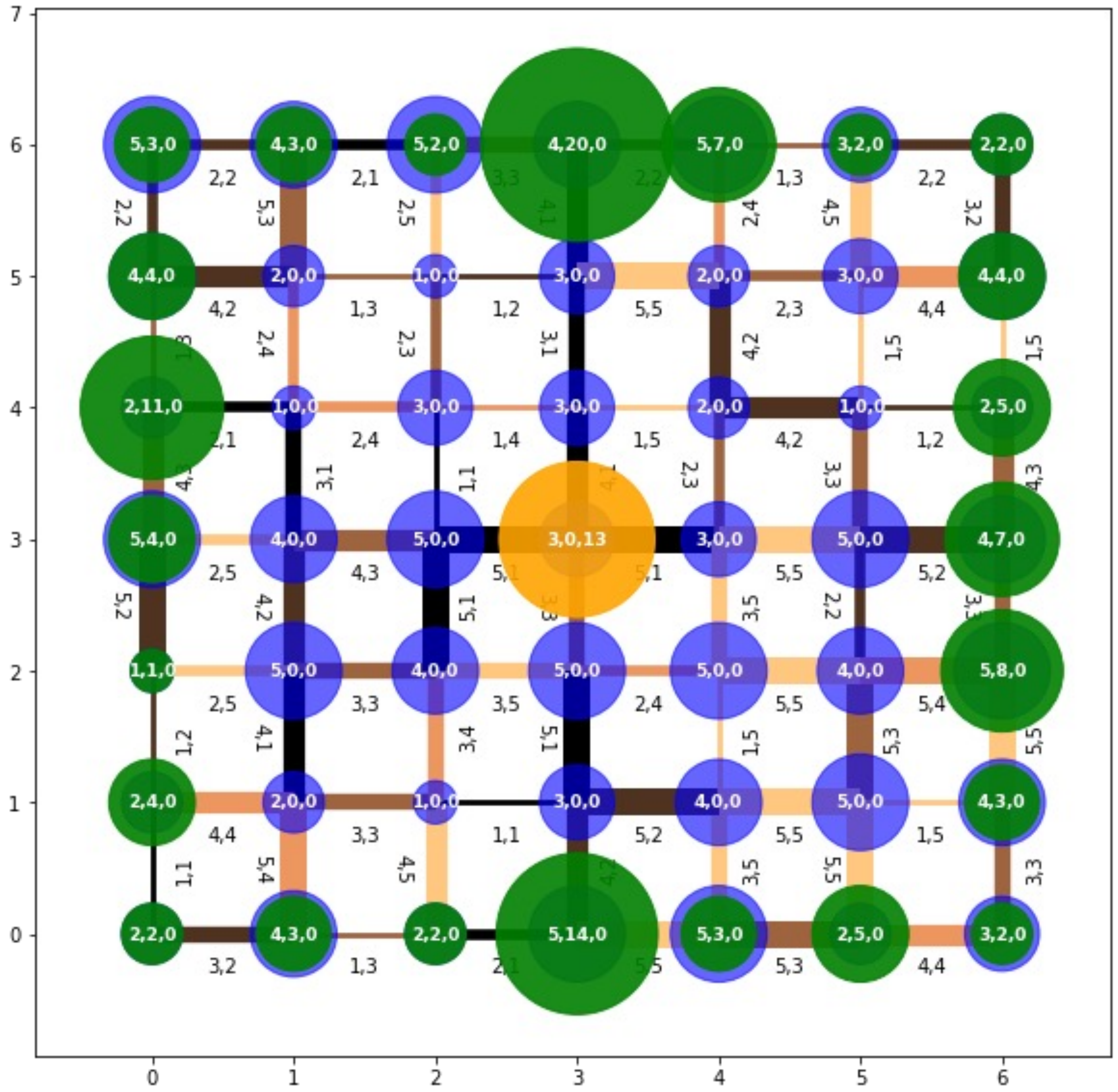
Output evacuation plan


getStage
route : dict
party : dict
flow : dict
time : int
applyCCRP
source : list
time : int
MPCCRP
+ DrawGraph: obj
+ Party: obj<dict>
+ Population: ogj <dict>
+ Route: obj <dict>
DrawGraph
+ nodes: list
+ edges: list
+ popN: dict
+ CapN: dict
+ timeE: int
+ capE: dict
Poputlation
+ source: list
+ popN: dict
+ timeE: int
Route
+ graph: dict
+ nodes: list
+ weight: int
Party
+ party: dict
+ popN: dict
+ party_info: list
setNodePop
node : list
party : dict
popN : dict
time : int
getNodePop
node : list
party : dict
time : int
party_dijstra
graph : dict
source : list
target : str
weight : int
getRoute
node : list
party : dict
edges : list
getPartyN
popN : dict
removePartySuper
party : dict
addPartySuper
capE : int
party : dict
timeE : int
get_SD
type : str
shape : list
gen_grid2D
shape: list
makeCCEdges
capE : int
timeE : int
makeCCNodes
capN : int
timeE : int
makeCCGraph
graph_type: str
getEdgeTime
route : dict
edges : list
getResE
route : dict
time : int
edges : list
getResN
route : dict
time : int
nodes : list
getPathFow
route : dict
party : dict
time : int

Simulations



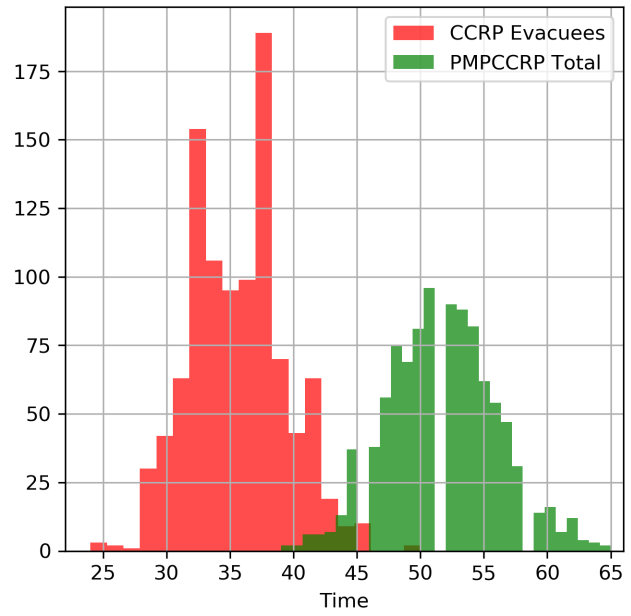
Endangered Capacity Constraint Graph

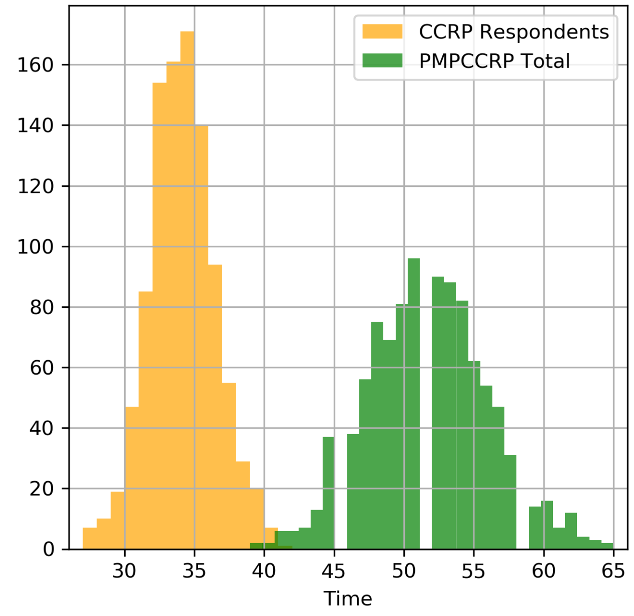


Evacuated Capacity Constraint Graph

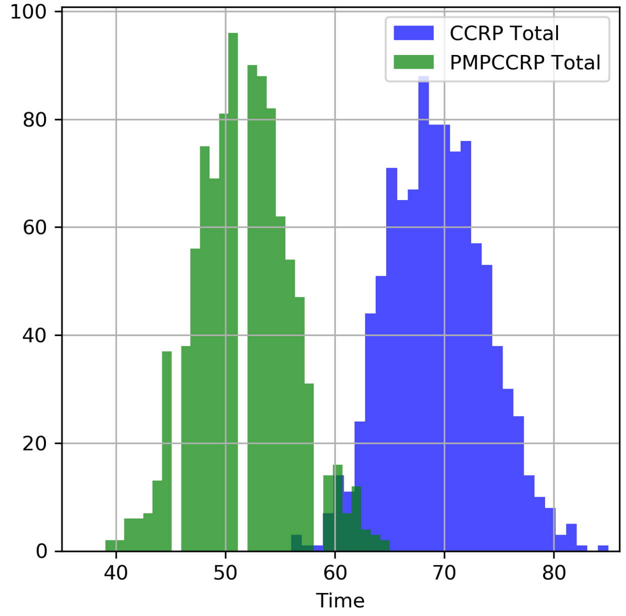
Experiments and Results

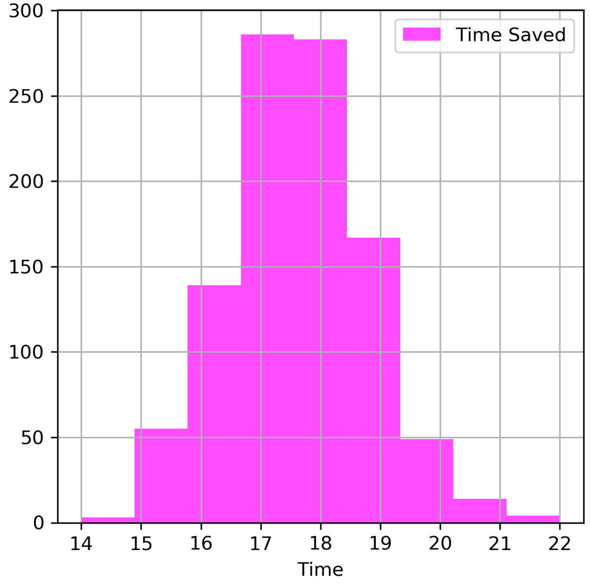
- For test trial, generate a *9-by-9* Manhattan grid network
- Run simulate 1000 times on network
- Max node capacity: 5 - 10
- Max Arc Capacity: 3 - 5
- Travel times : 3 - 7
- Initial Pop: 3 to max node capacity
- Each node has 50% chance of including responder





	mean	std	min	25%	50%	75%	max
CCRP-EVA	35.654	3.752	24	33	36	38	50
CCRP-RESP	33.643	2.375	27	32	34	35	42
CCRP-TOTAL	69.297	4.682	56	66	69	72	85
PMP-CCRP	51.715	4.356	39	49	52	55	65
POP	451.4	17.00	395	441	452	462	505





Research Contribution

- ❖ The cell transmission model which was limited to only small networks was improved by developing network conversion model (NTC), to convert any size node-arc network into cell network.
- ❖ We proposed and applied the dynamic cell-transmission evacuation planning (DyCTEP) model to large scale networks to give better global solutions.
- ❖ We then incorporated arc-congestion, which is a situation where the speed at which the system empties is a decreasing function of cell/node occupancy y_i^t into the model formulation, to mimic the bottlenecks on the streets in the real-life evacuation processes.
- ❖ We proposed a Heuristic Algorithm for optimal route assignment taking into consideration all network optimal flow dynamics captured in time.
- ❖ We proposed and implemented three new approaches, namely Dynamic Earliest Arrival Flow, Extended CTM and the Multiple Cells Approaches to cope with the inconveniences associated with DyCTEP.
- ❖ Finally, we proposed the priority multi-party capacity constrained route planning a heuristic algorithm and an extension of the CCRP by Shekhar et al. The proposed PMP-CCRP is equipped with the ability to plan for the evacuation of multiple parties with different objectives. That is, evacuees may begin their journey from an endangered source and travel to a safe destination, while inversely emergency responders may begin their journey from anywhere and travel to a dangerous location. It ensures that during the evacuation process, priority is given to high-risk areas, that is, evacuees in highly endangered zone are evacuated first before those in less risky areas.

Future Research

- The future work will be the incorporation of the methods, algorithms and procedures described in this thesis in a novel smart city service that is able to guide evacuees and rescuers after a disaster to bring to safety as many people as possible out the risky and endangered places.

- The service must be fed by real-time information (which roads are safe enough, which are damaged by the disaster, how many people are in a specific area, and so on).

- Starting from our proposed algorithms, we plan to be able to specify, design and implement a smart city infrastructure and connected mobile app able to collect all the needed data. These together with the proposed algorithms will realize the rescue and evacuation service for smart cities of the future.

- We are studying to incorporate additional risk factors into the model, like those associated with each node and/or each arc/street.

- We also want to research on the development of a hybrid approach for evacuation planning by performing a mesoscopic study, where we try to factor the human behaviour in order to understand some individual interactions between pedestrians during evacuation.

- In the case of the multi-party capacity constrained route planning discussed, we are researching to include an examination on N number of party's interaction and route planning times.

- Another feature valuable for real-life emergency coordinators would be an ability to apply weighted priorities to better address the non-uniform urgency and importance each party brings regarding the larger scheme of things.

Research Publications

- **Published:**
  - Evans Etrue Howard, Pasquini Lorenza, Arbib Claudio, Di Marco Antinisca and Clementini Eliseo "Definition of an Enriched GIS Network for Evacuation Planning". *In Proceedings of the 7th International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2021), pages 241-252*
  - Ghulam Mudassir, Evans Etrue Howard, Lorenza Pasquini, Claudio Arbib, Antinisca Di Marco, and Giovanni Stilo "Toward Effective Response to Natural Disasters: a Data Science Approach" . *In IEEE Access 2021, volume 9, pp.167827-167844.*
  - Evans Etrue Howard, Antinisca Di Marco and Claudio Arbib "Towards an Emergency Evacuation Planning Service". *7th Italian Conference on ICT for Smart Cities And Communities, 2021*

- **In progress:**
  - Evans Etrue Howard, Pasquini Lorenza, Arbib Claudio, Di Marco Antinisca and Clementini Eliseo *"Automatic generation of evacuation plans from real GIS data"*
  - Evans Etrue Howard, Antinisca Di Marco and Claudio Arbib. *"Mapping knowledge structure and research trends of Pedestrian Emergency Evacuation Models: A State of the Art."* The entire literature reviewed is based on this article.

Thank You