

# Q-RES MARL

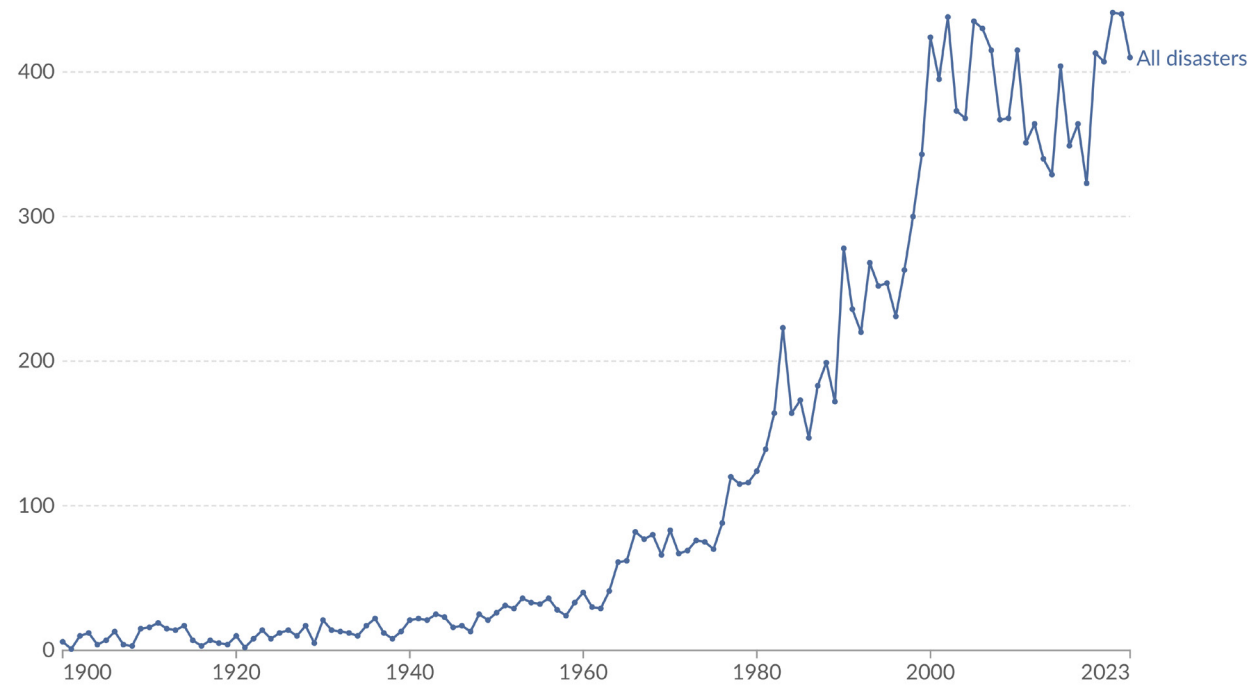
*A Resilience-Based MARL Framework for the Post-Earthquake Recovery of Interdependent Infrastructures*

Antonios Mavrotas - AR3B05 - P5 Presentation - 23/06/2025

*Mentors: Charalampos Andriotis and Simona Bianchi  
Invaluable assistance was also provided by Prateek Bhustali*

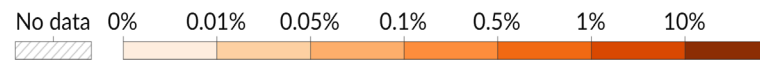
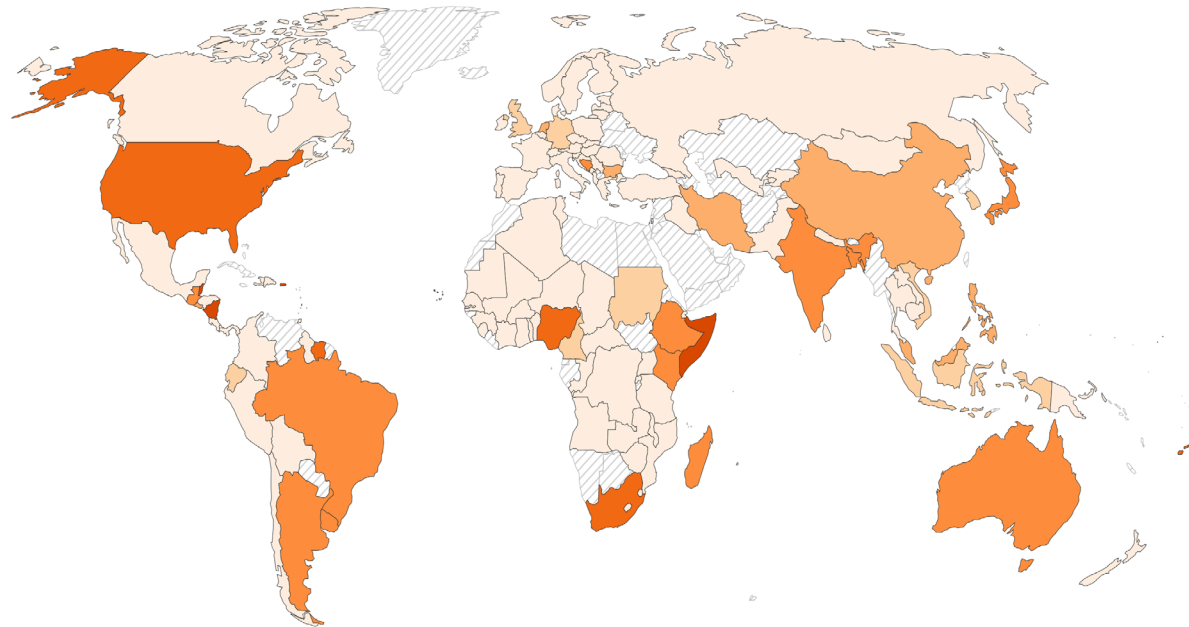
## *Natural Disasters: Wider Urban Impacts on Built Environment*

## Increasing Disaster Frequency



Disaster Frequency / #

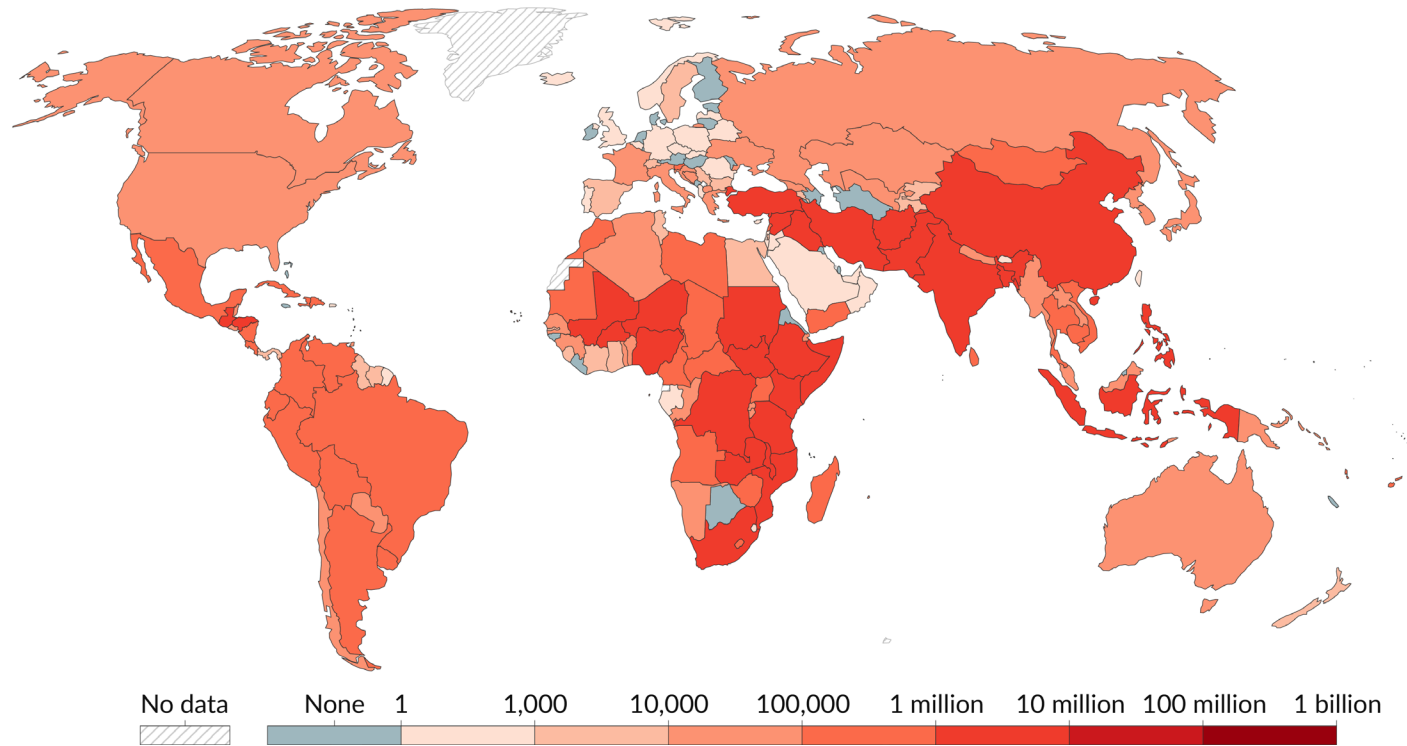
## Significant Economic Shocks



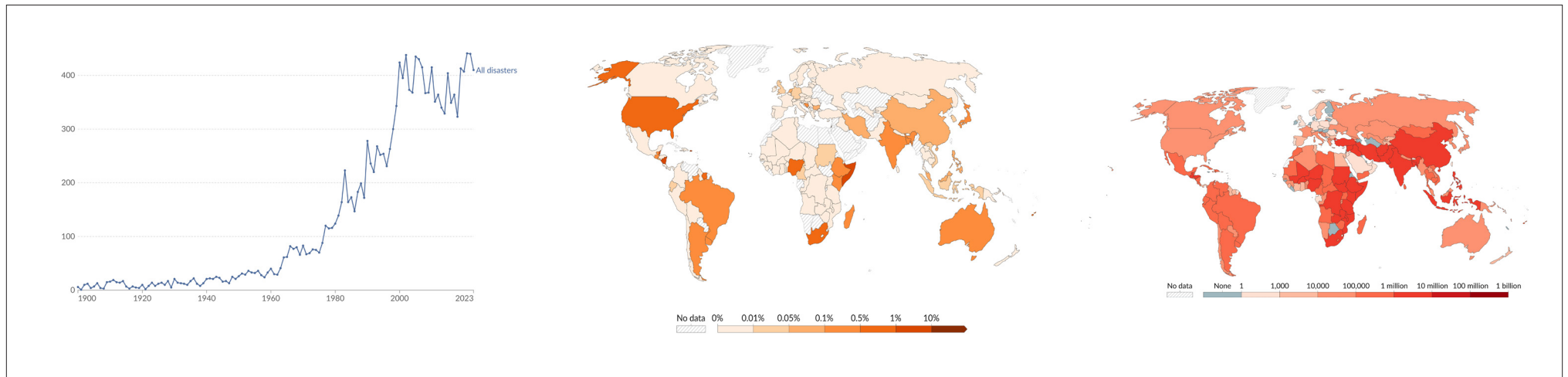
*Economic Losses / % GDP / yr*



## Exceeding Human Losses

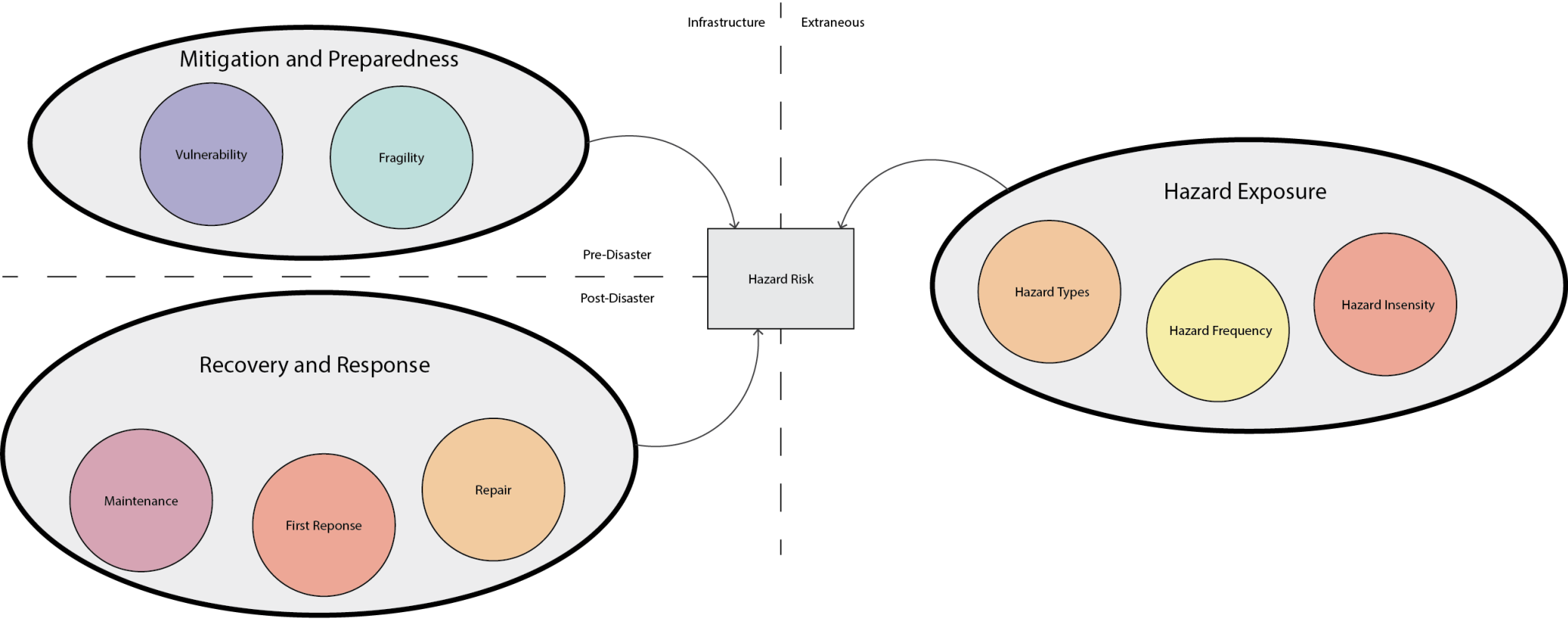


# people req. assistance (2019)

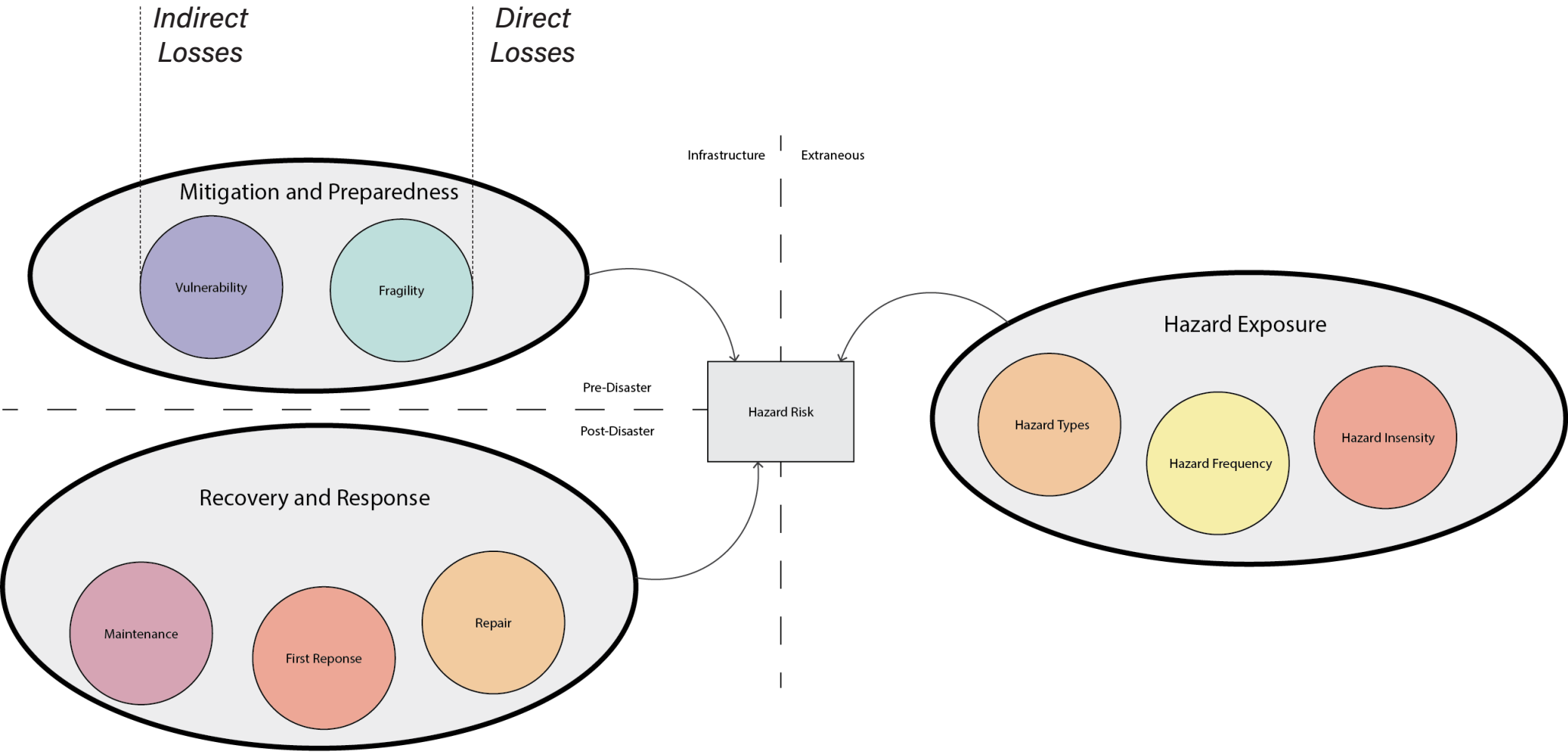


*Increased Global Hazard Risk*

*Hazard Risk Contributors*



*Hazard Risk Contributors*





## Examples of Damage



### *Landslide in Switzerland*

*Buildings are dependent on the damage from debris of neighbouring buildings.*



### *Flash floods in Spain*

*Cascading effects of vehicle debris on traffic.*



### *Earthquake in Morocco*

*Lack of centralised planning in rural areas makes government financing challenging.*

*What are Interdependencies?*



## Interdependencies

Health  
Network



Electrical Power  
Network



Visibility and Rescue Operations affected by Smoke  
by Electrical Substation

Transportation  
Network



Building  
Portfolio



Road Capacity is Dependent on Building Debris



2023 Inskenderun Earthquake, Turkey

## *How Can We Predict Damage To Infrastructure?*



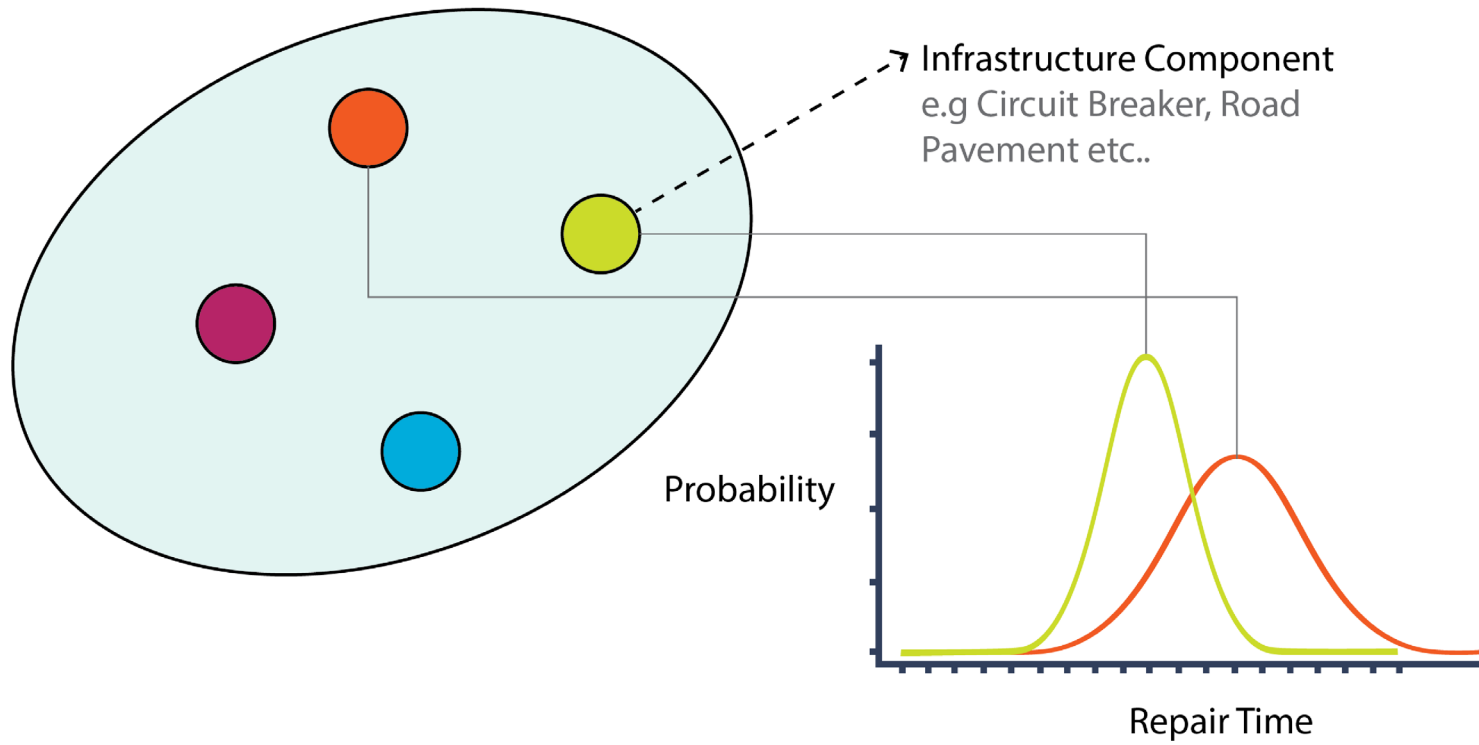


## *Large Scale Damage Prediction*



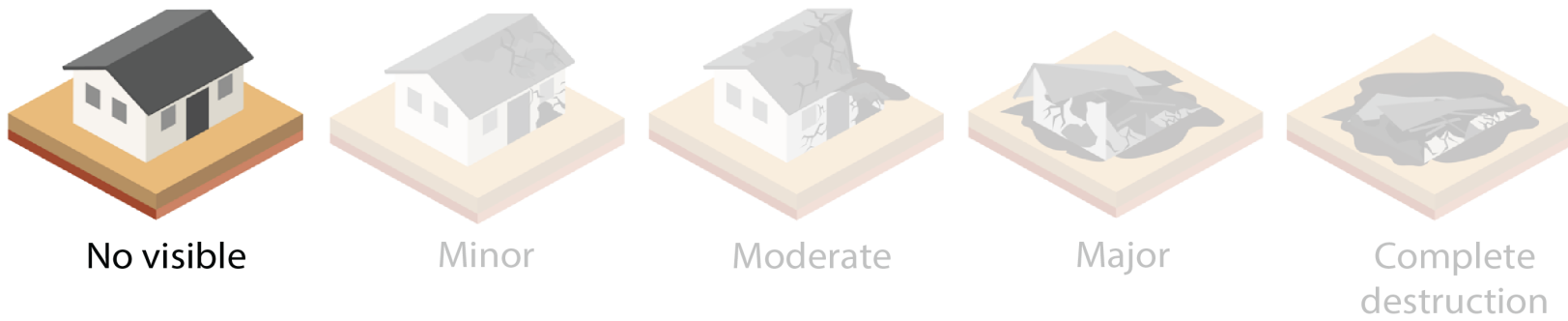
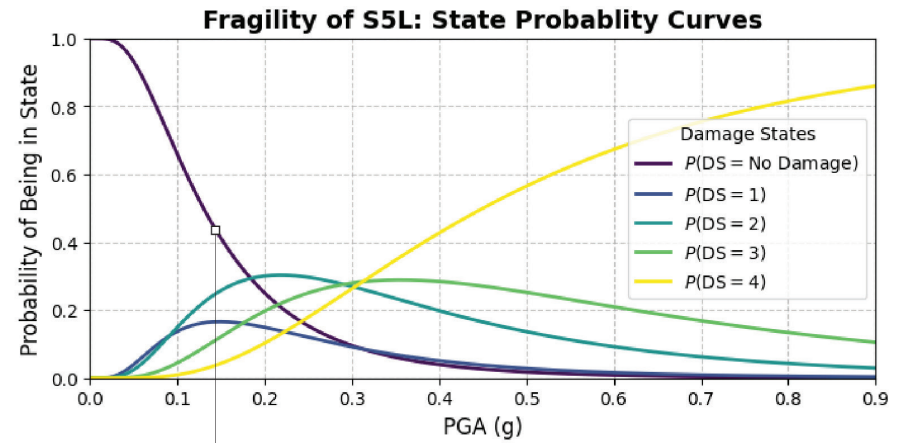
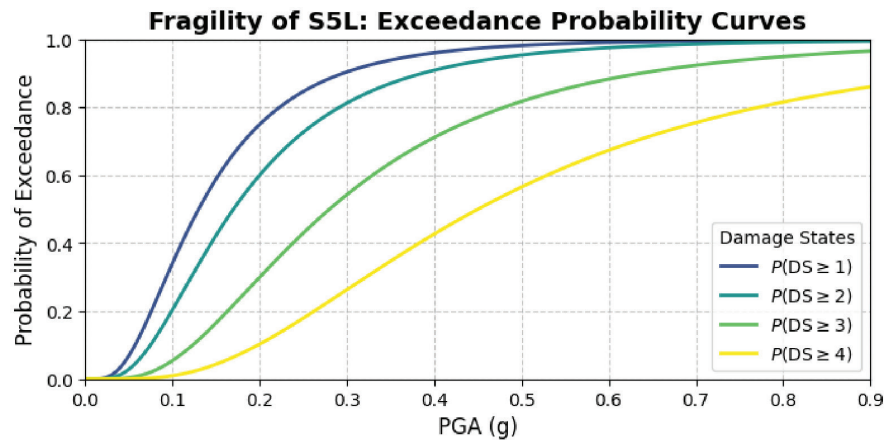
*Infrastructure in Anaheim, US.*

## Stochastic Damage Prediction

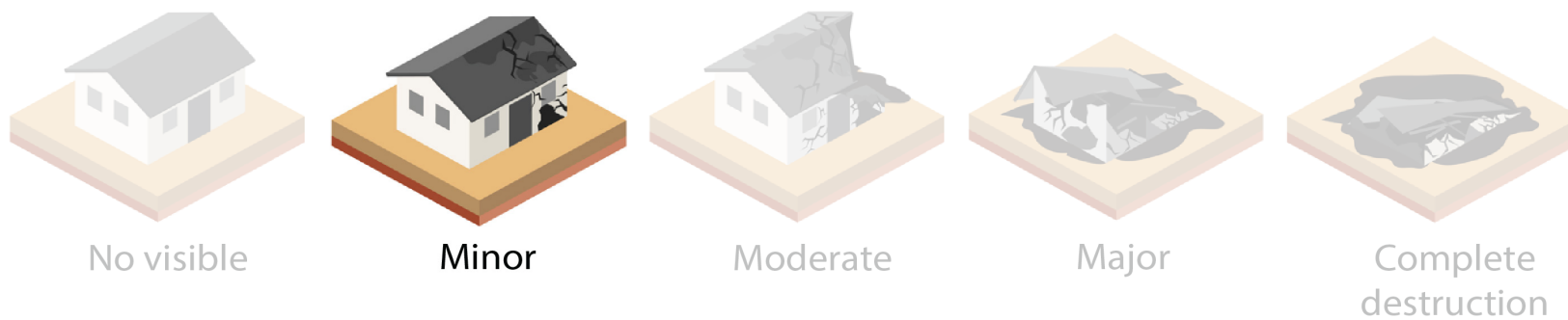
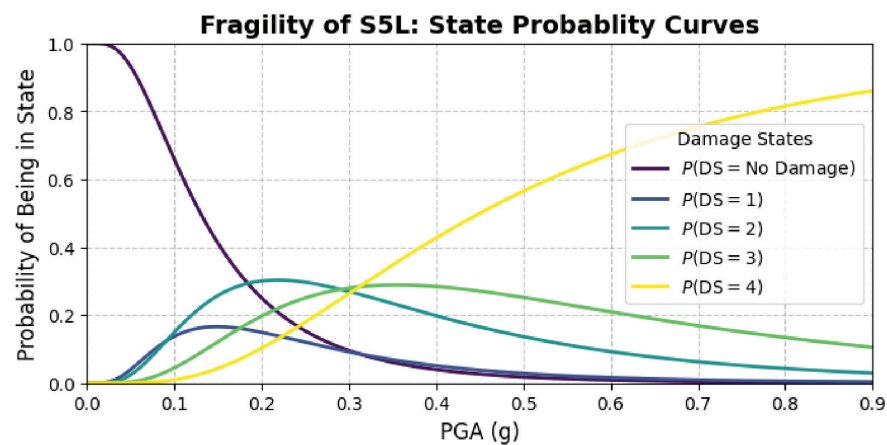
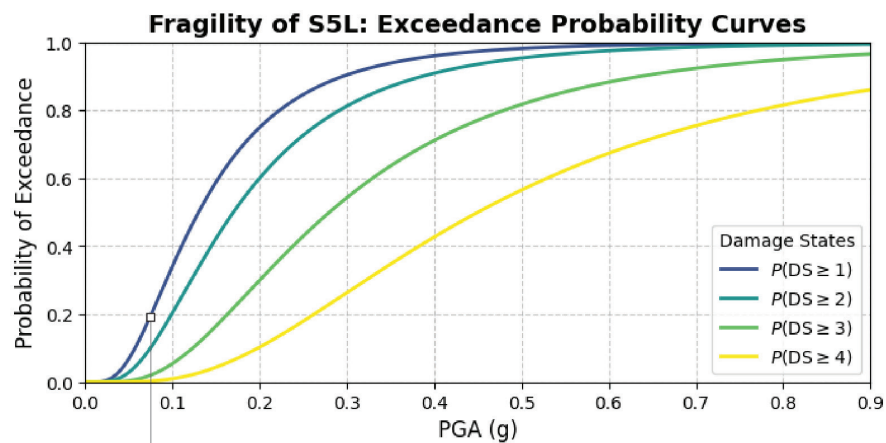




## Fragility Curves

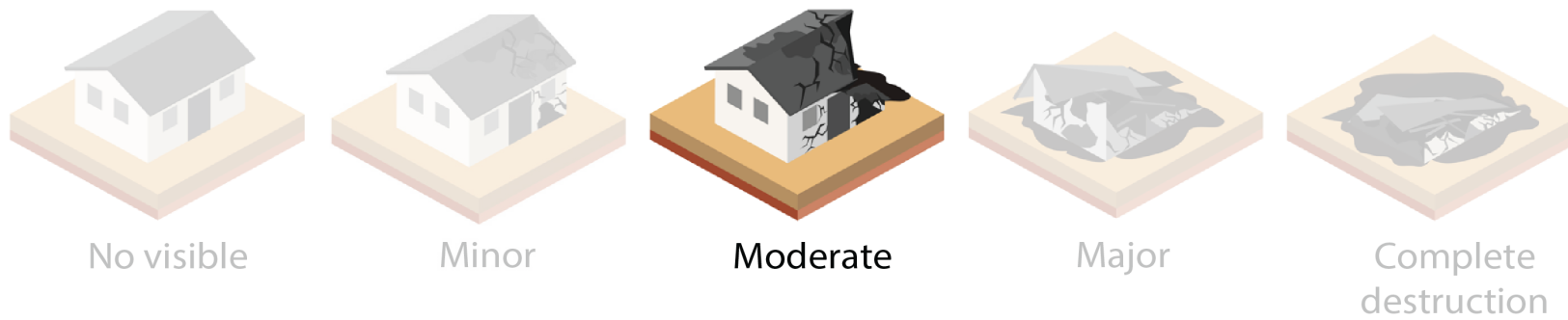
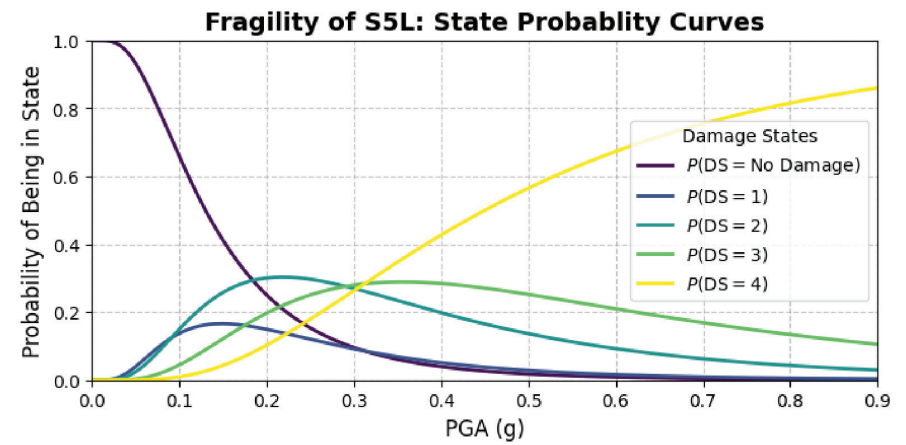
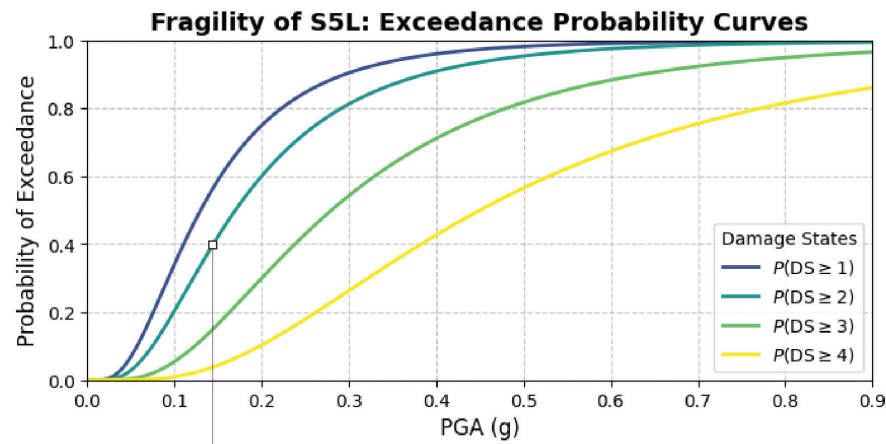


## Fragility Curves

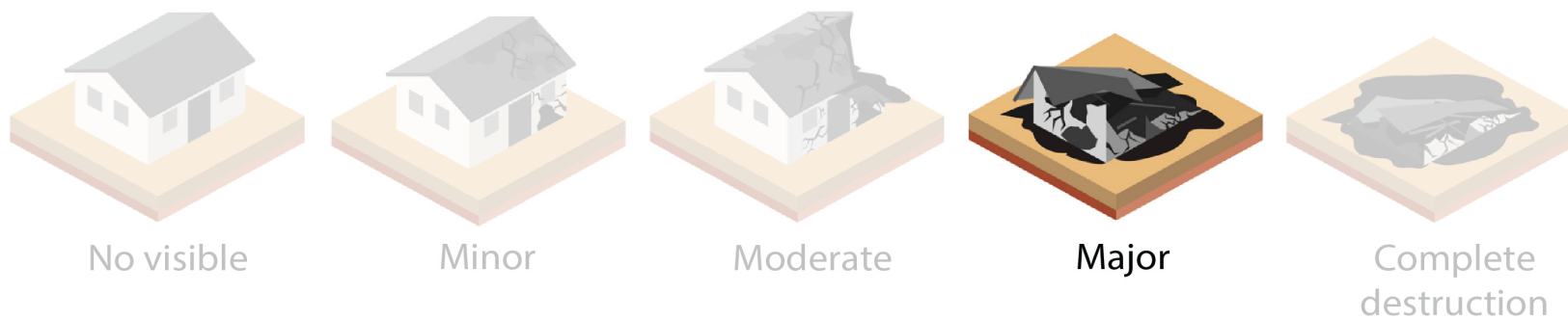
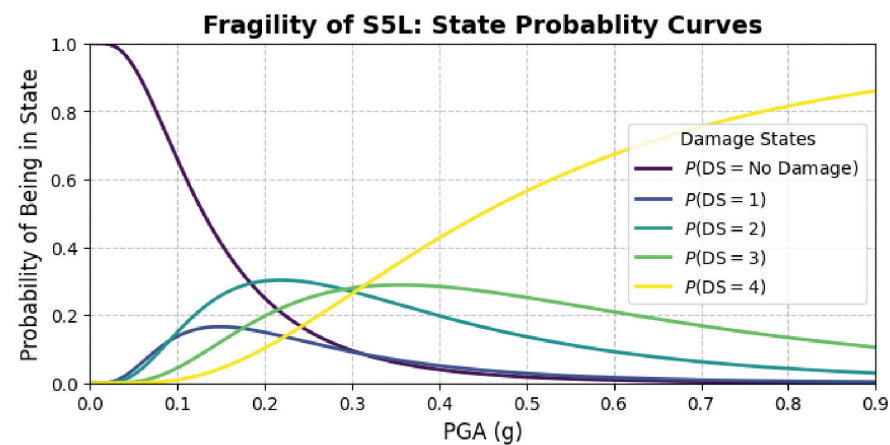
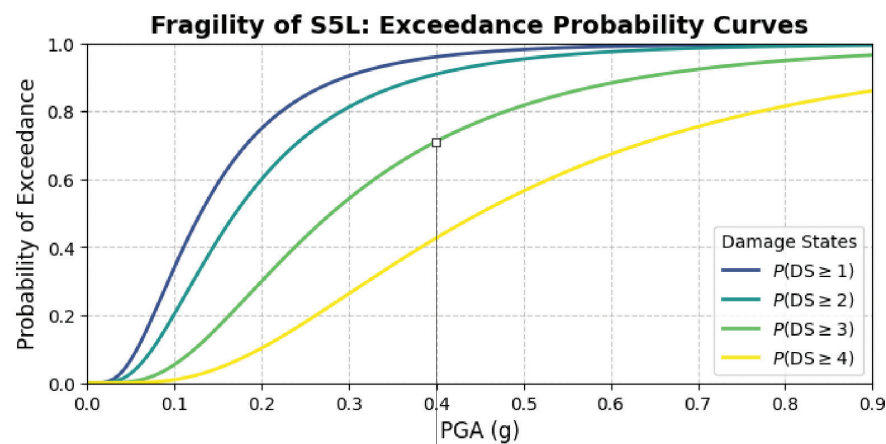




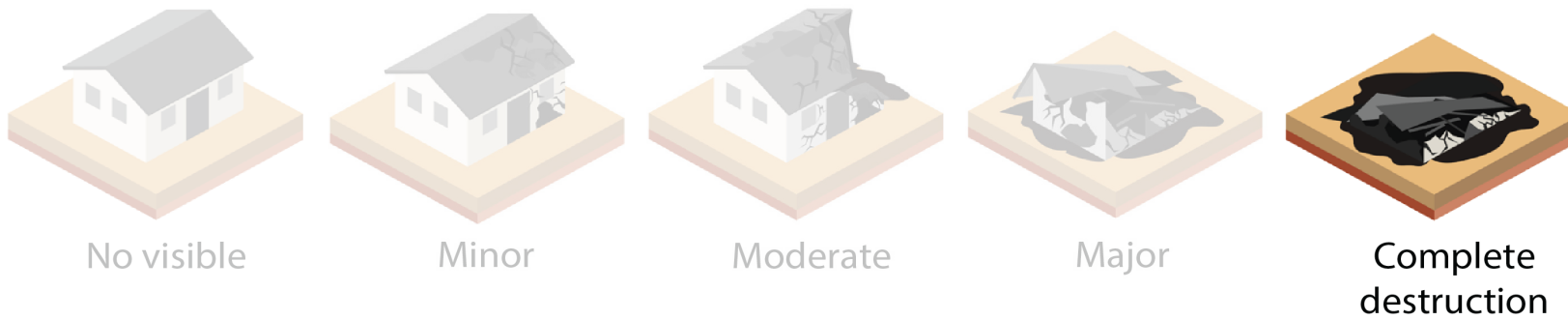
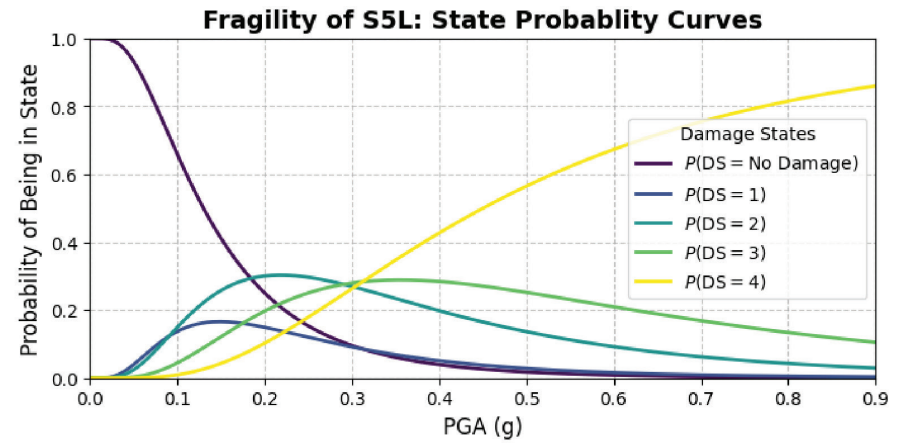
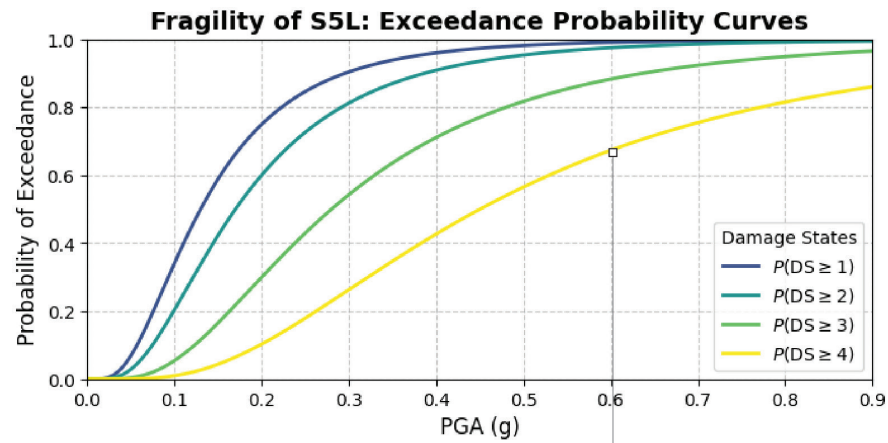
## Fragility Curves



## Fragility Curves



## Fragility Curves



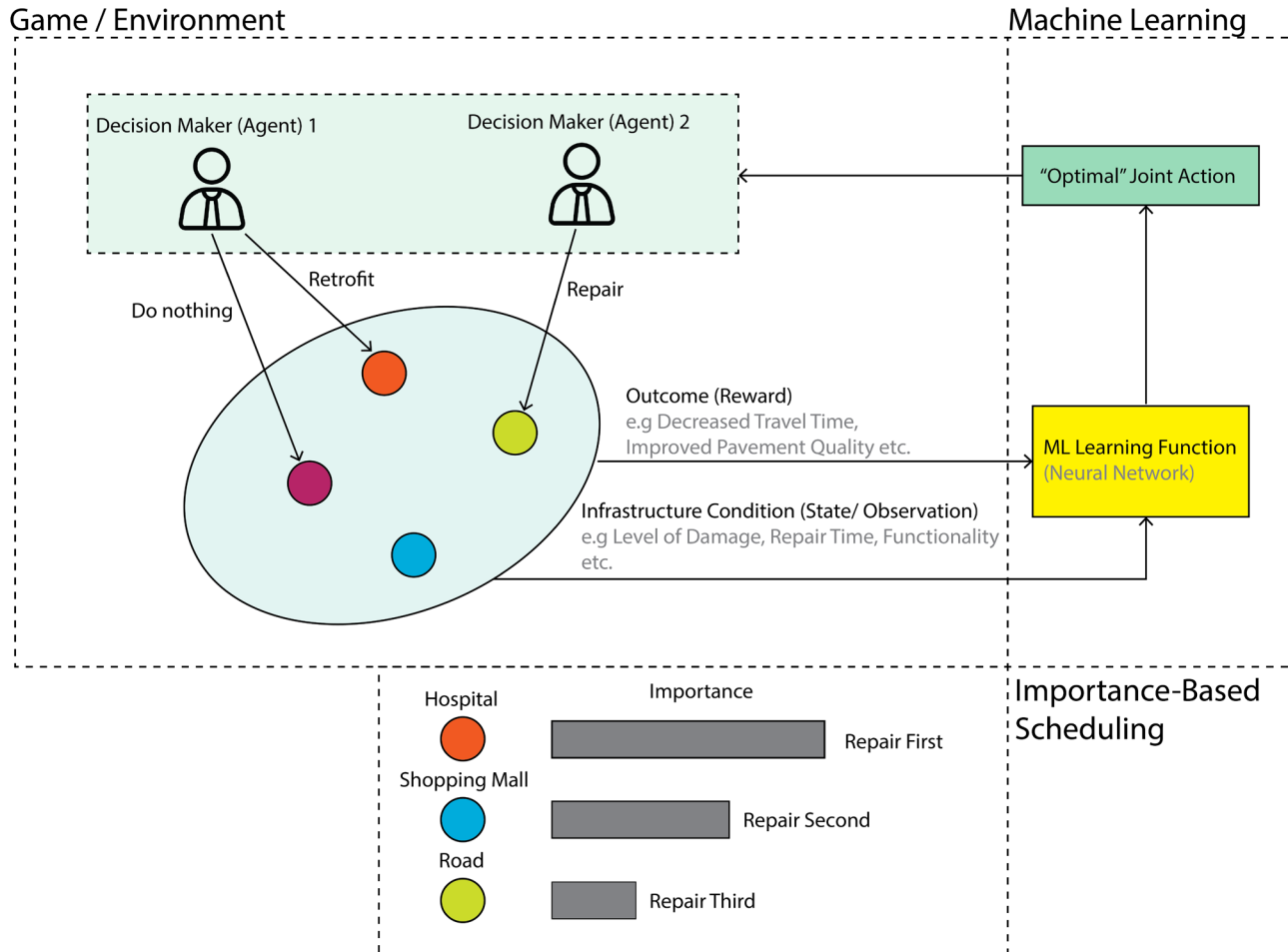
## *Devising Optimal Repair Strategies*





# Hypothesis

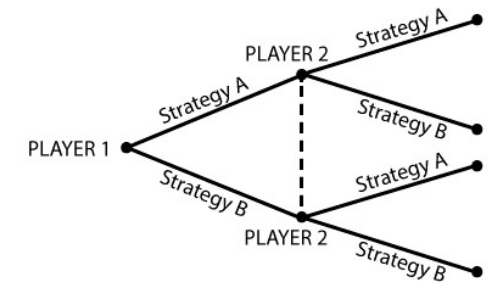
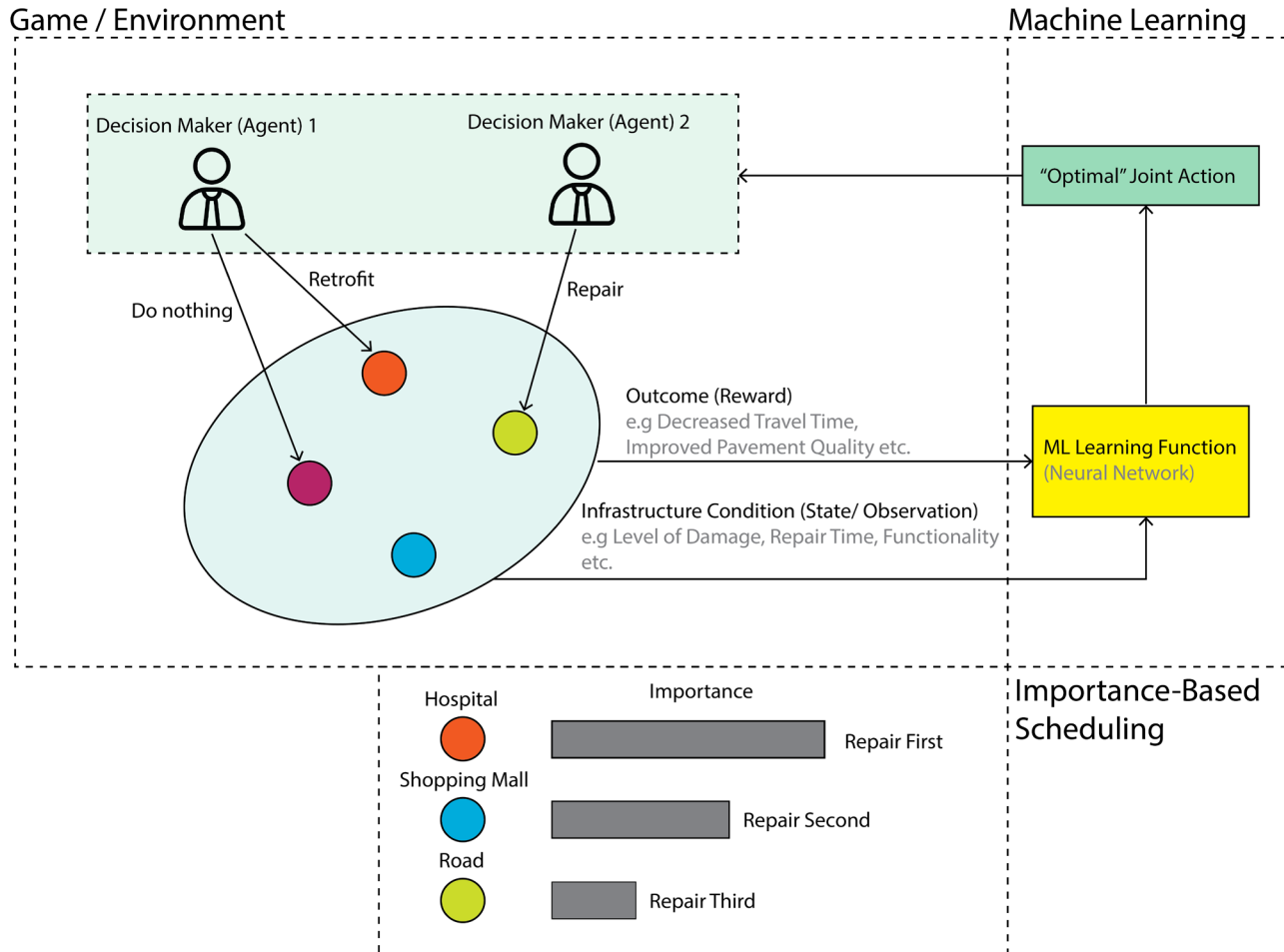
*MARL can perform better than Importance-based repair scheduling of interdependent infrastructure networks.*



*MARL vs Importance-Based decision making*

# Hypothesis

*MARL can perform better than Importance-based repair scheduling of interdependent infrastructure networks.*



*Players, Decision Makers = Agents*

$$\text{Importance Index} = \frac{dem(t)}{cap(t)}$$

$$\text{Performance Index} = \frac{q(t)}{q^*(t)}$$

*Examples Of General Importance-Based Ranking*

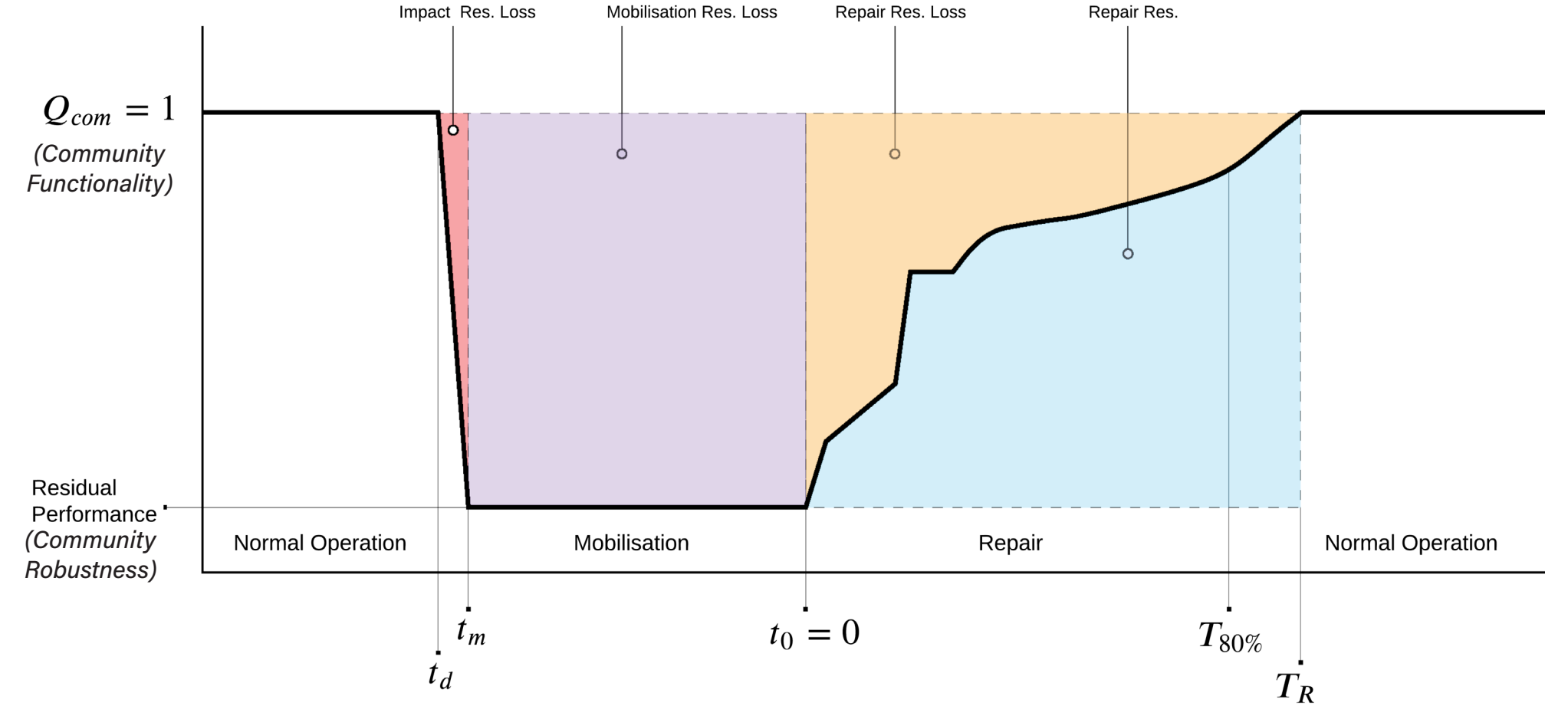
*MARL vs Importance-Based decision making*

## *How Do We Measure The Success Of A Repair Policy?*



Measuring Success With Resilience

$$Q_{com} = \sum_i^{i=N_{sub}} w_i \cdot q_i(t)$$



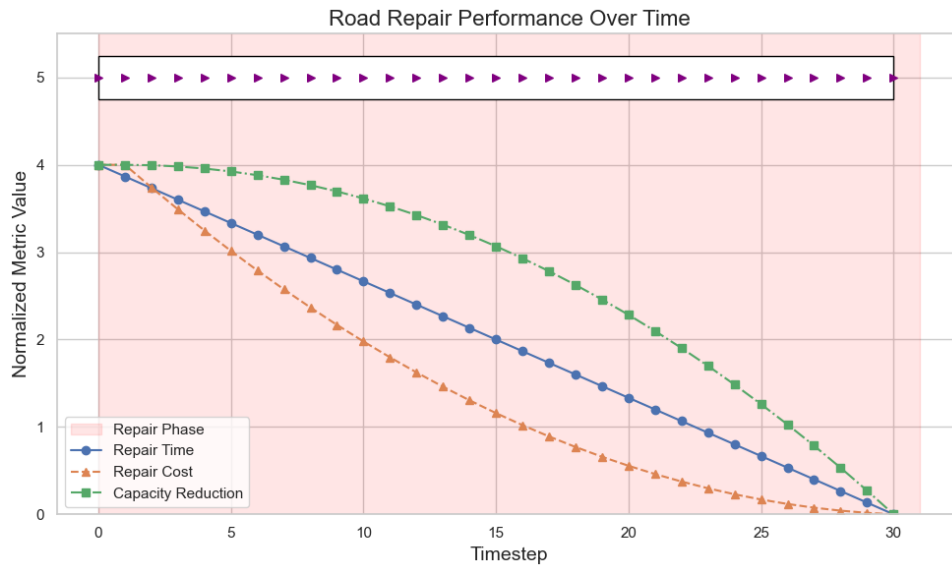
Community Functionality / Time

## Measuring Functionality

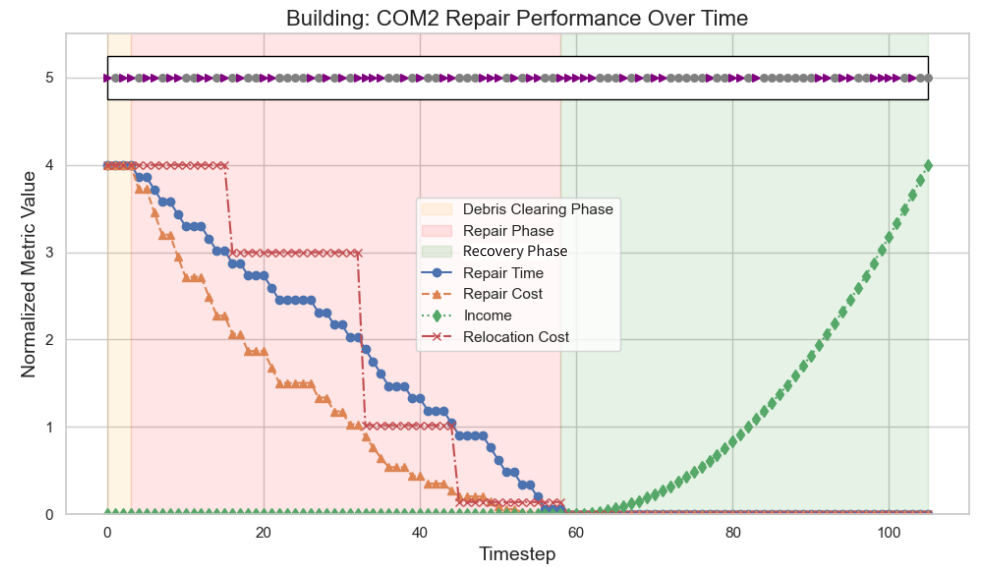
$$\text{Community Functionality } Q_{com} = \sum_{i=1}^{N_{sub}} w_i \cdot q_i(t)$$

$$\text{Sub-system Functionality } q_i(t) = 1 - L_i(t)$$

$$\text{Sub-system Loss } L_i(t) = \frac{C_i(t)}{C_i^+(t)}, \quad 0 \leq L_i(t) \leq 1$$

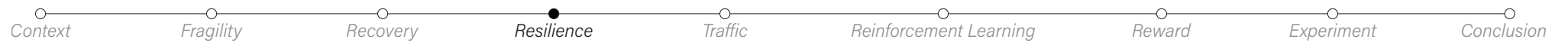


Optimal Repair (Repair at Every Timestep) of a Highway Road Segment



Sub-optimal Repair (Random Intervention at Every Timestep) of a large shopping mall

## *Methodology*





**Data**

OpenStreetMaps OR Custom Testbed  
National Structures Inventory OR Custom Testbed

Attenuation Model  
Quake Epicenter  
Quake Parameters  
Study Sites

INCORE API  
Ground Motion Prediction Equations

**Environment**

Reset - sample earthquake

Building Intensity Measures  
Building Portfolio  
Road Intensity Measures  
Transportation Network

HAZUS Recovery Data  
HAZUS Fragility Data

Road Recovery Indicators  
Road Damage Status  
Road Functionality  
Building Damage Status  
Building Recovery Indicators

Road Baseline Capacities  
Damage Extent  
Road Obstructed Capacities  
Traffic Assignment  
MTT  
Mean Travel Time

Custom Traffic Network and Demand  
TATP Ben Shaker

**Resilience**

relocation  
Population Relocation Costs

buildings  
Building Repair Costs

income  
Current Income

health  
Available Doctors and Hospital Beds

critical  
Functioning Critical Facilities

Qecon  
Economic Functionality

Qhealth  
Healthcare Functionality

Qcrit  
Critical Functionality

Qcomm  
Community Functionality

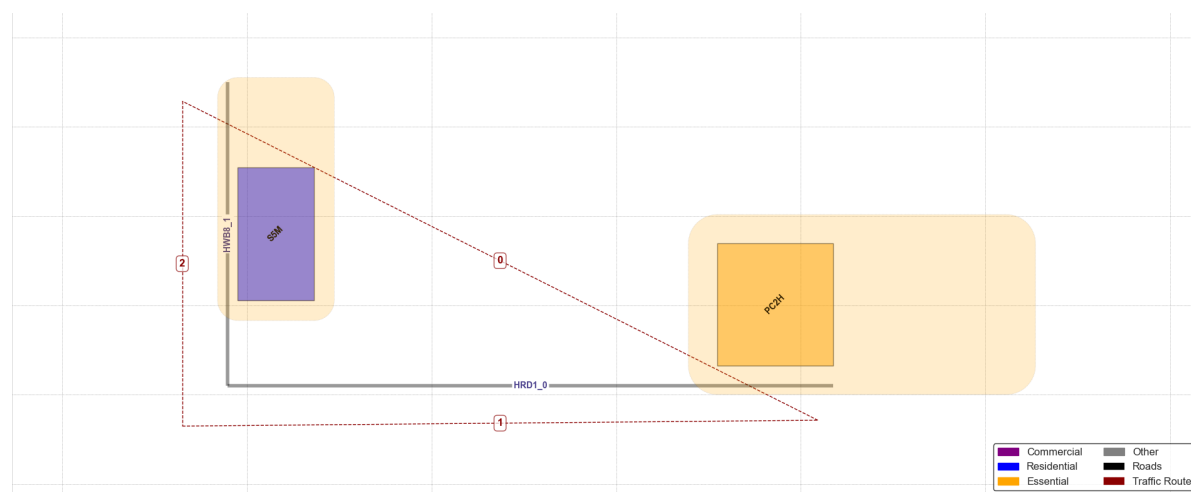
ΔMTT  
Traffic Delay

delay  
Traffic Delay Cost

roads  
Road Repair Costs

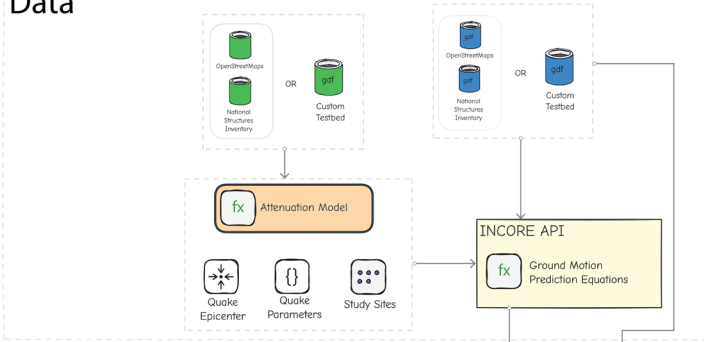
Context Fragility Recovery Resilience

*Toy City 30*

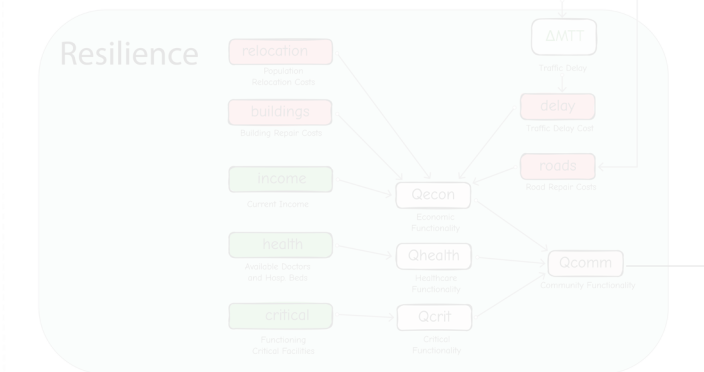
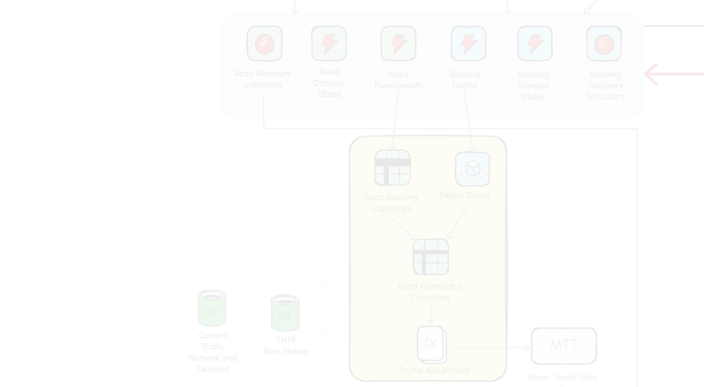


*Toy City 4*

## Data

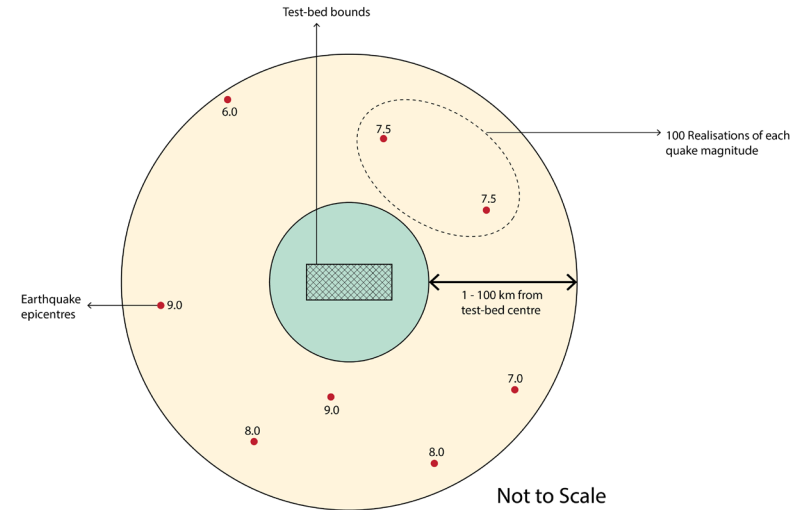


## Environment



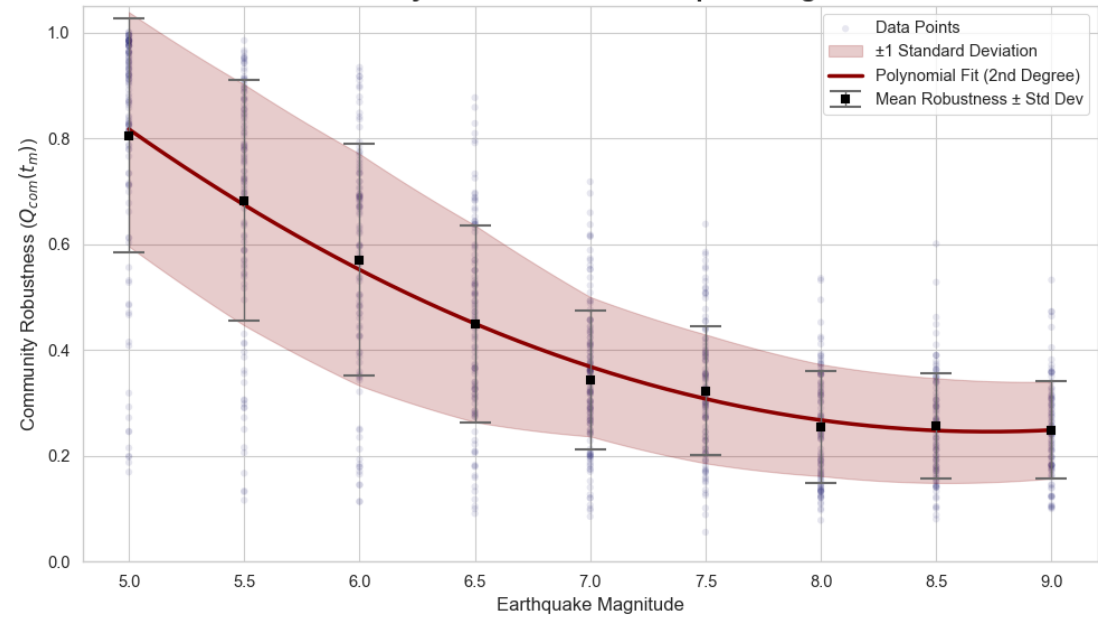
Context      Fragility      Recovery      **Resilience**      Traffic      Reinforcement Learning      Reward      Experiment      Conclusion

## Seismic Hazard Assessment



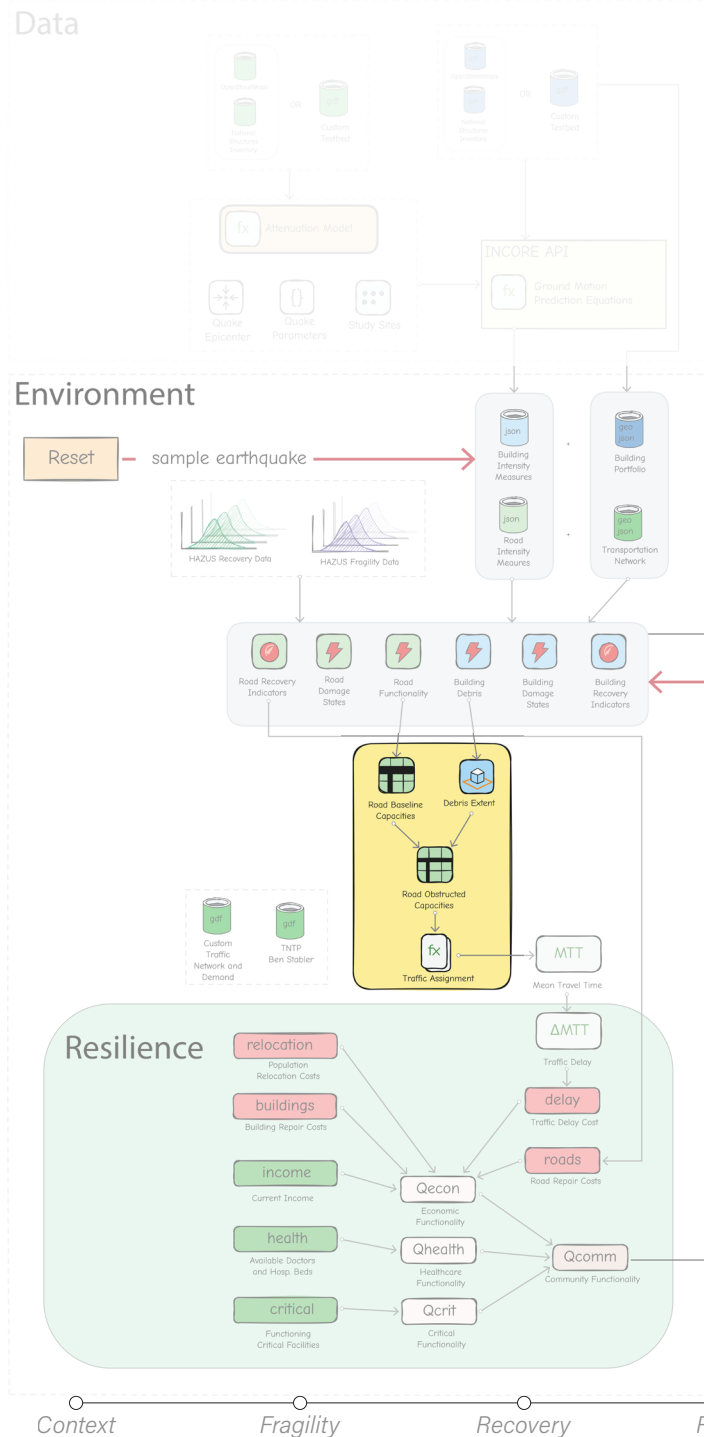
Dataset of Earthquakes from 5.0 - 9.0 M with 0.5 increments for 100 realisations per magnitude

## Community Robustness vs. Earthquake Magnitude

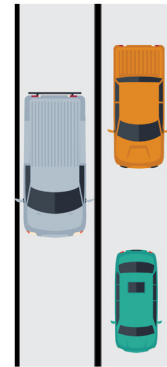


Results of Earthquake Impact to Community Functionality

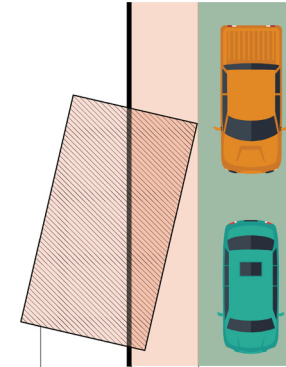
# Traffic



Undisturbed Traffic



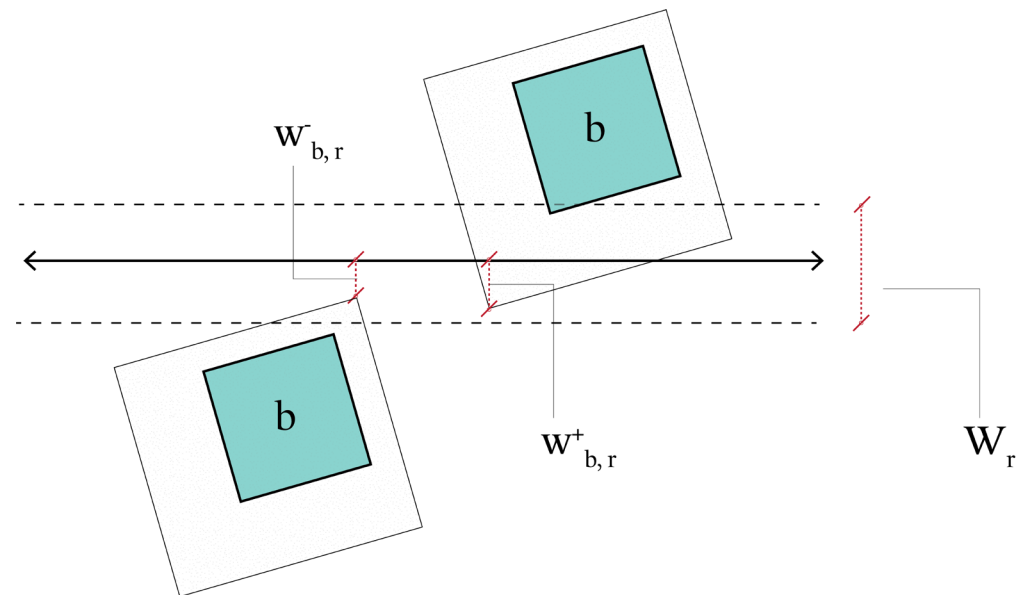
Disturbed Traffic



Building Debris

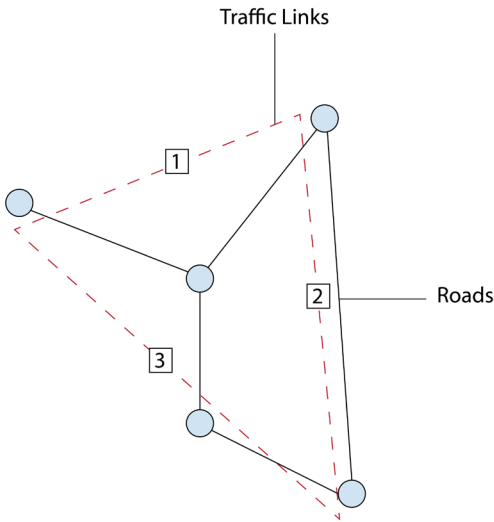
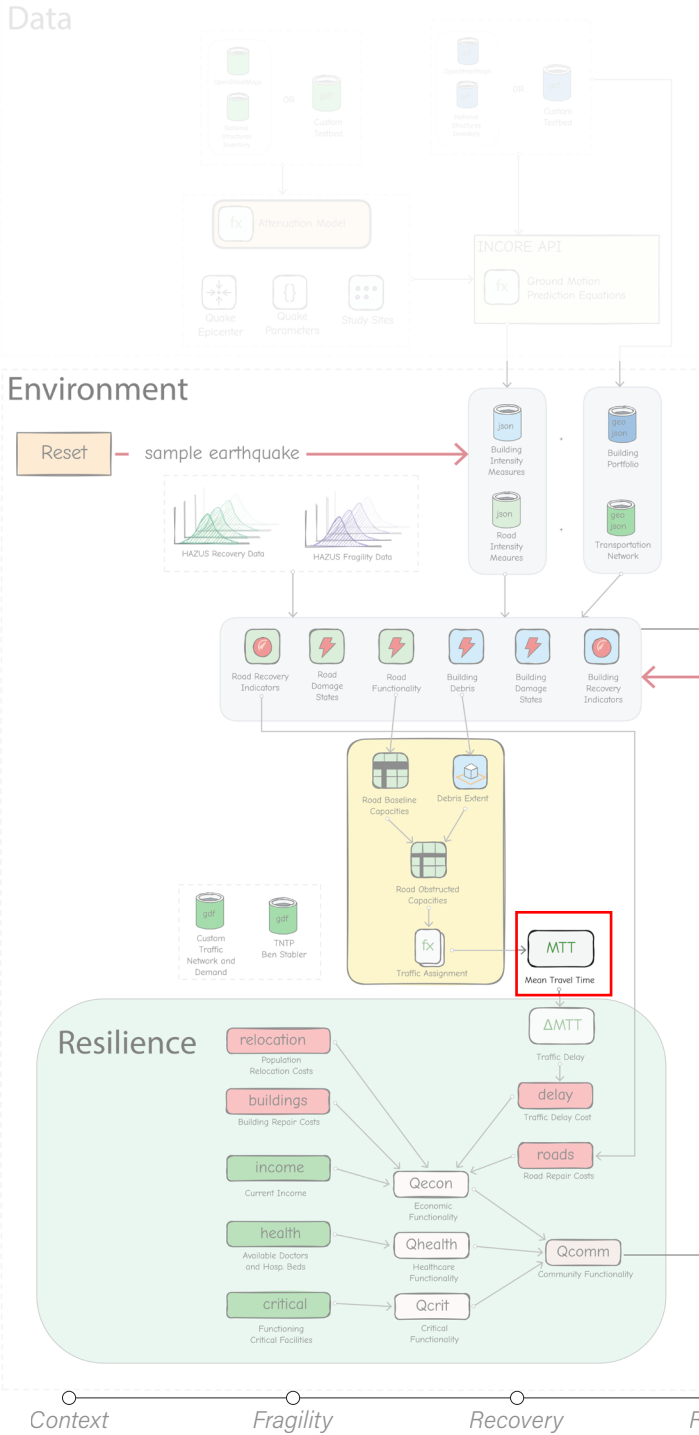
Effective Width

Effect of Debris on Traffic Link Capacity

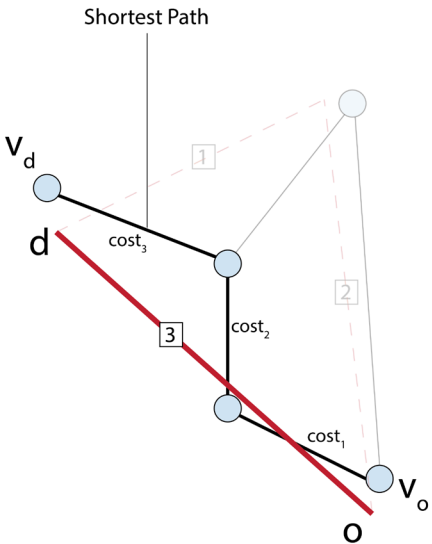


Traffic Link Capacity Calculation

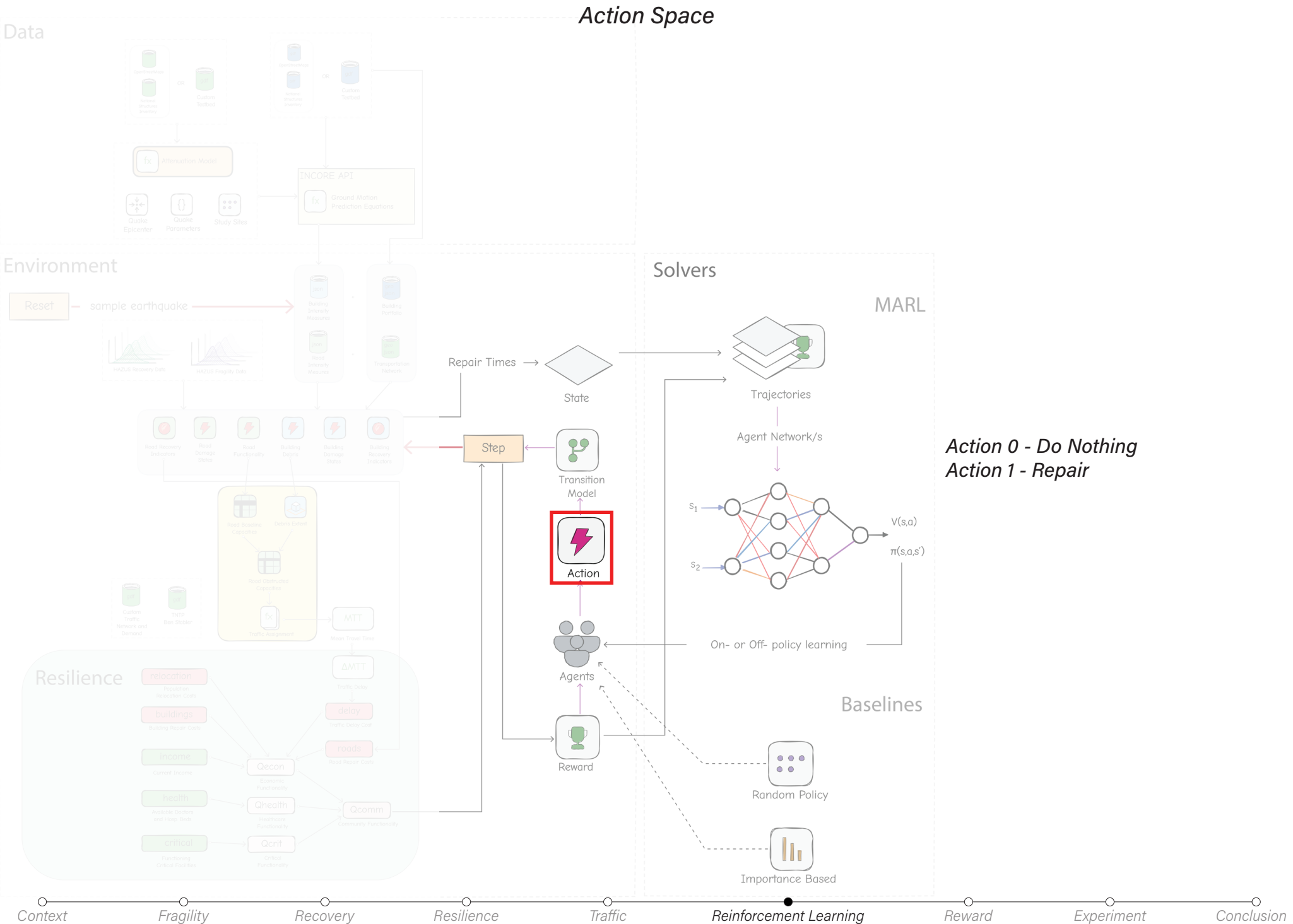
Traffic



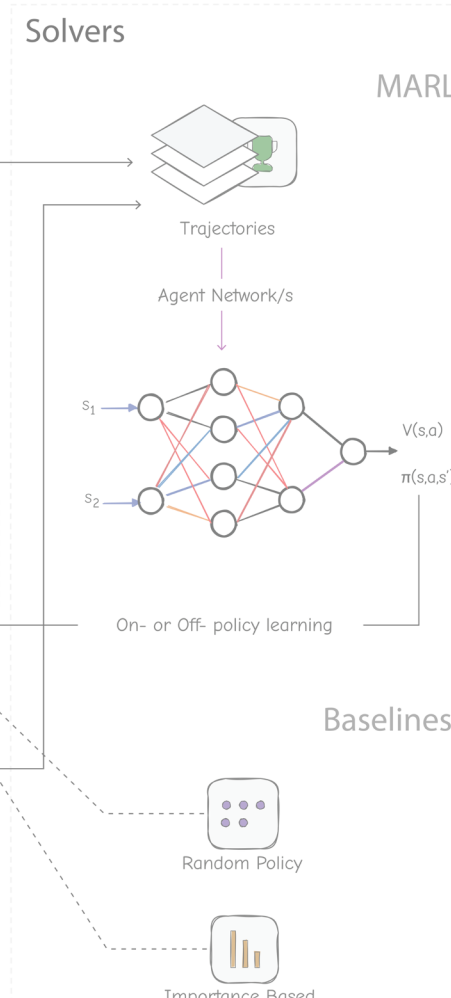
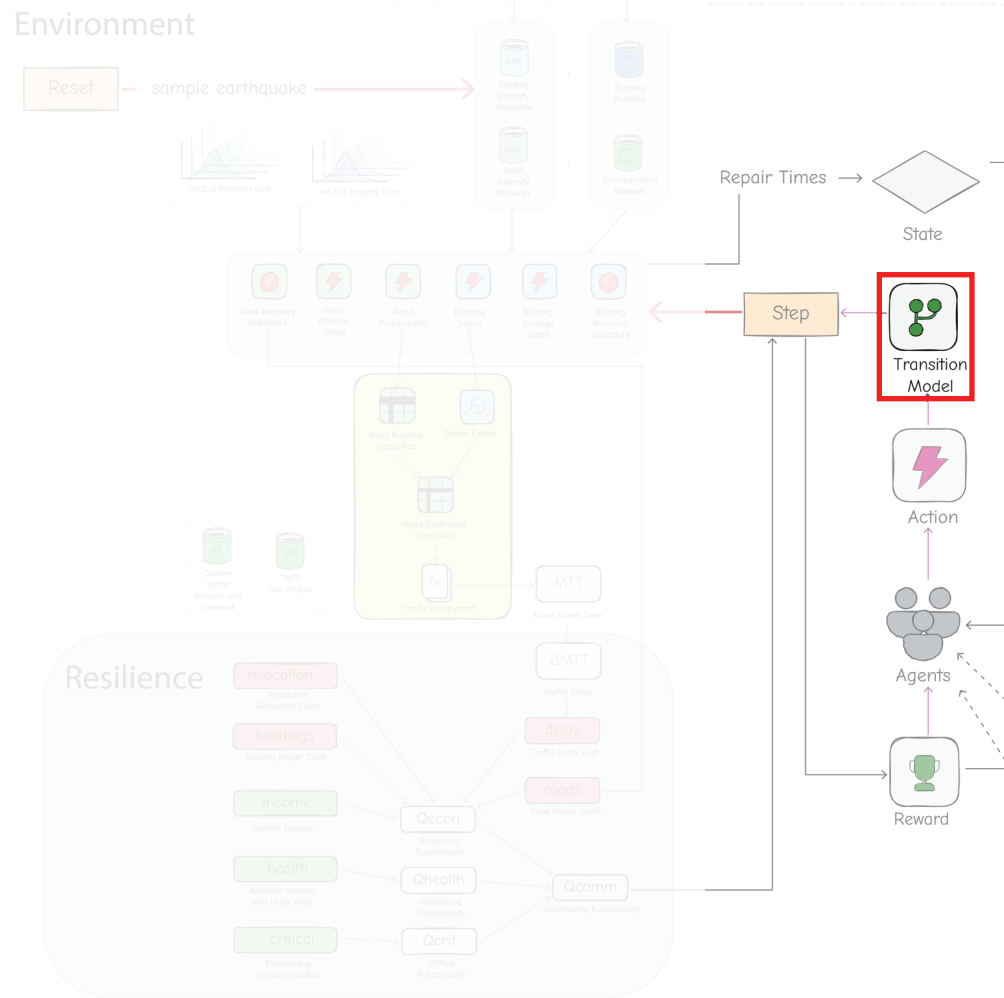
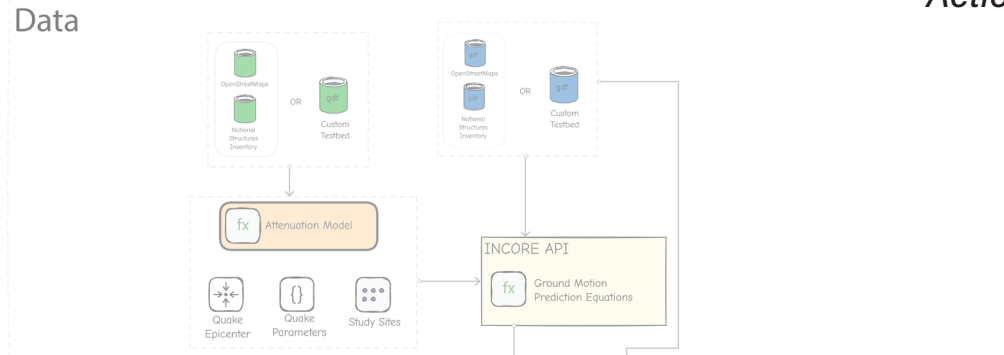
Traffic Link to Road Mapping







### Action Space

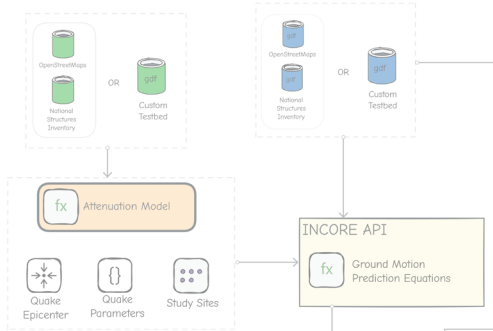


Road Repair Constraint  
Repair Crew Constraint

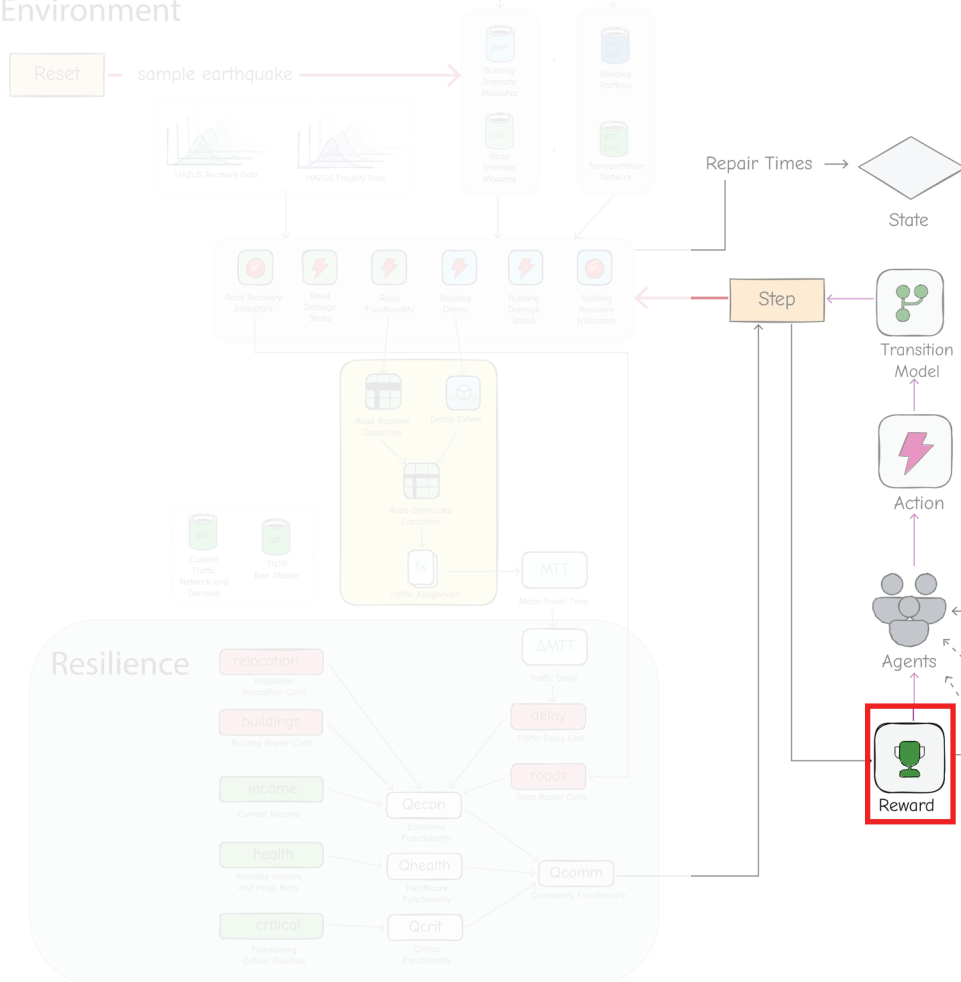


# Reward

## Data

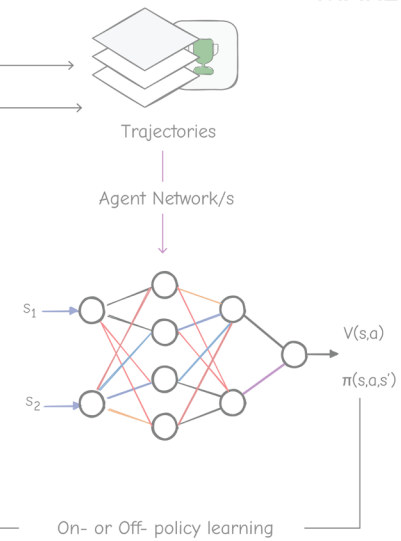


## Environment

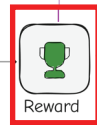


## Solvers

### MARL



### Baselines



Reward

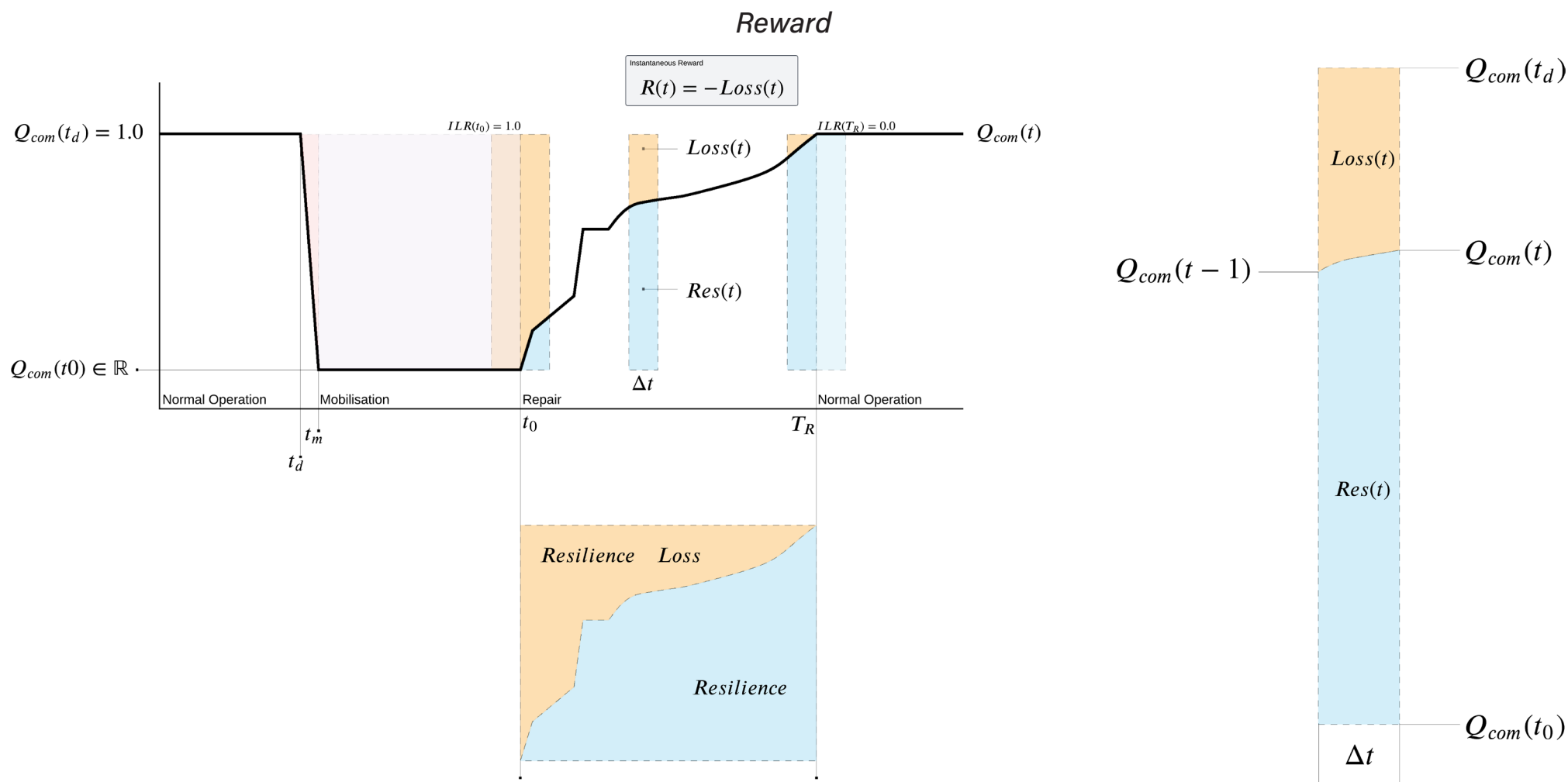
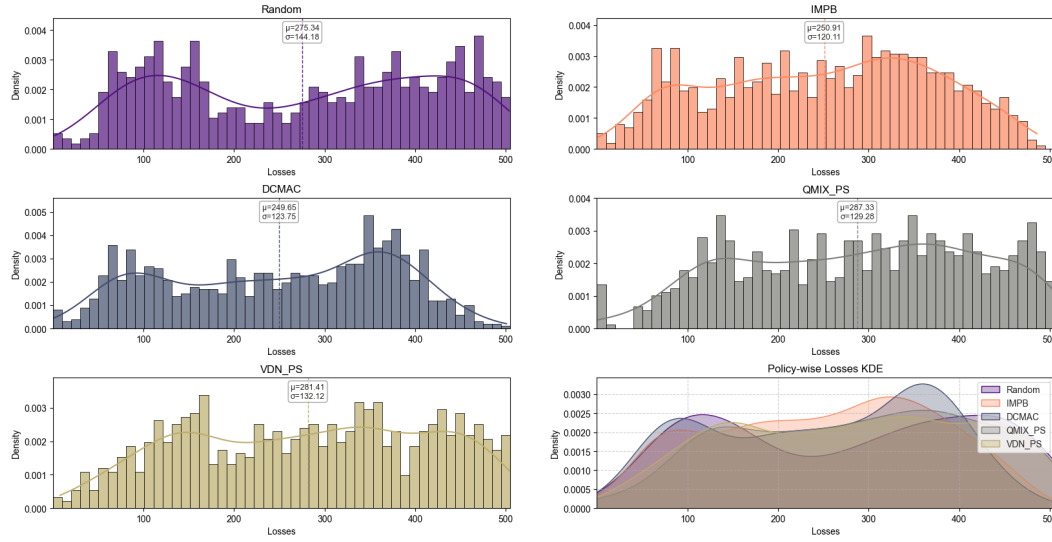


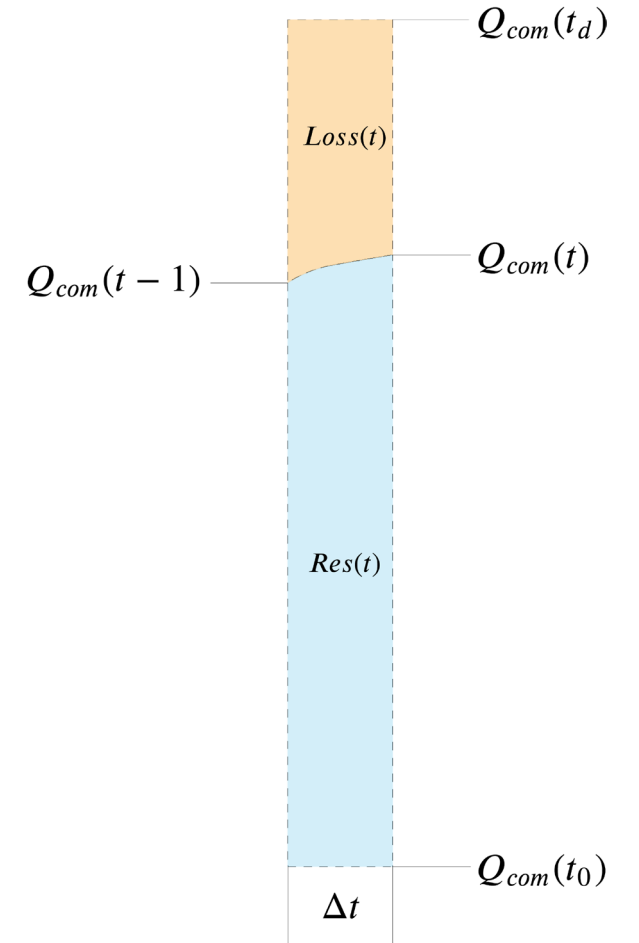
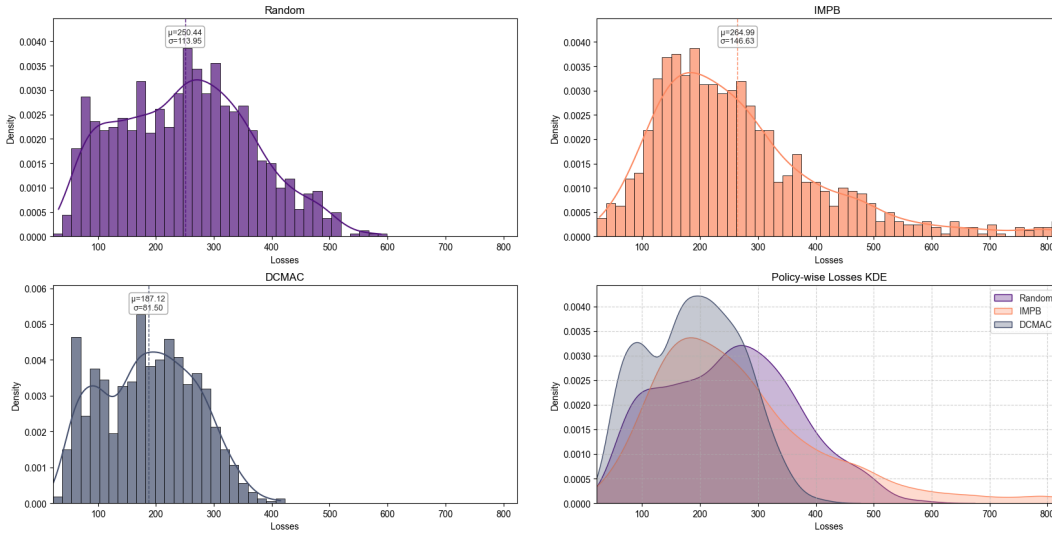
Illustration of Reward Function

# Results

**Cumulative Losses (CL) Distributions per Policy, over 1000 Rollouts, toy-city-4**



**70% Recovery Cumulative Losses (CL – 70) Distributions per Policy, over 1000 Rollouts, toy-city-30**





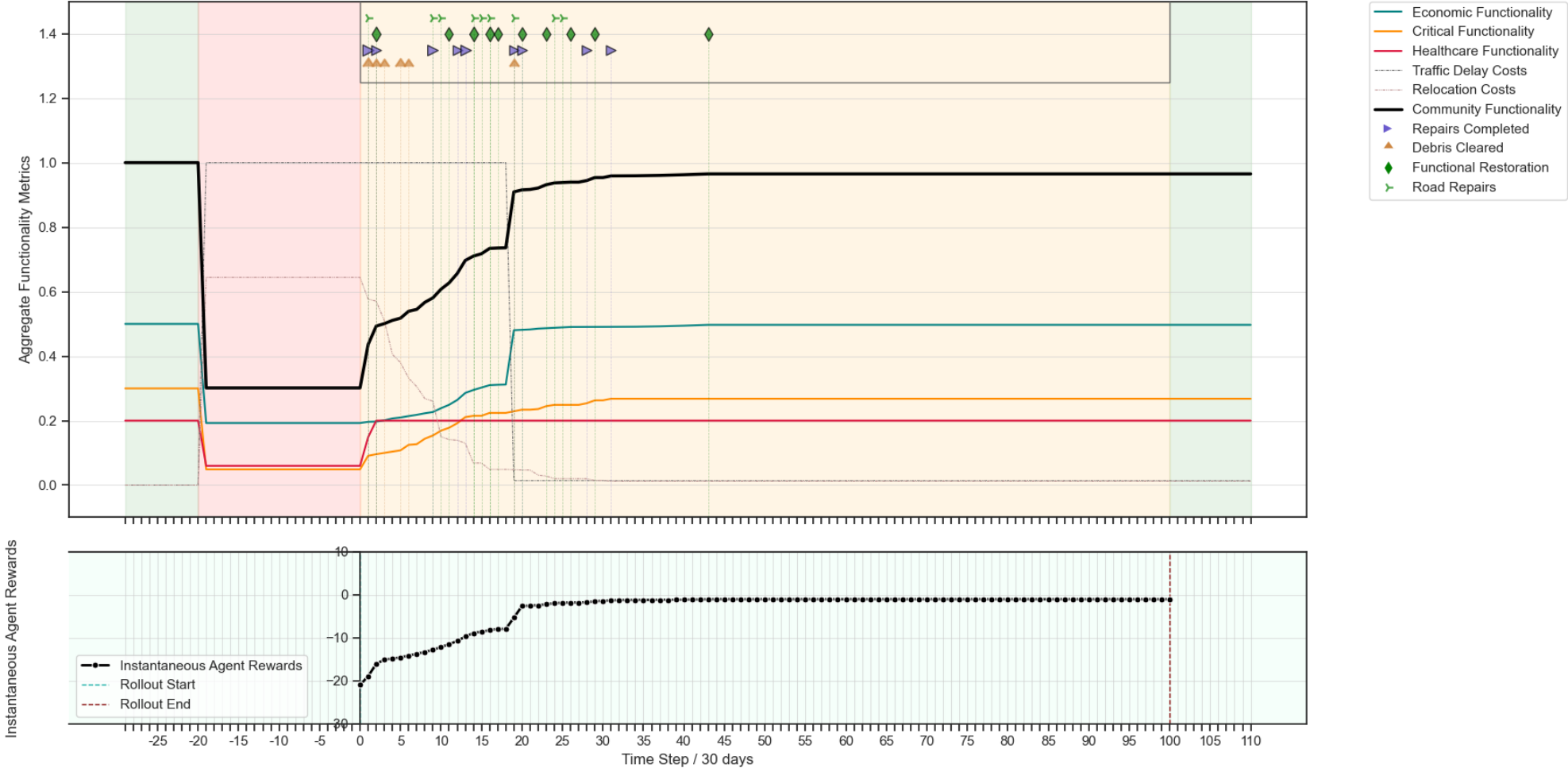
# Deep Centralised Multi Agent Actor Critic (DCMAC)

## Earthquake Repair Scheduling Rollout

toy-city-30

Policy: DCMAC

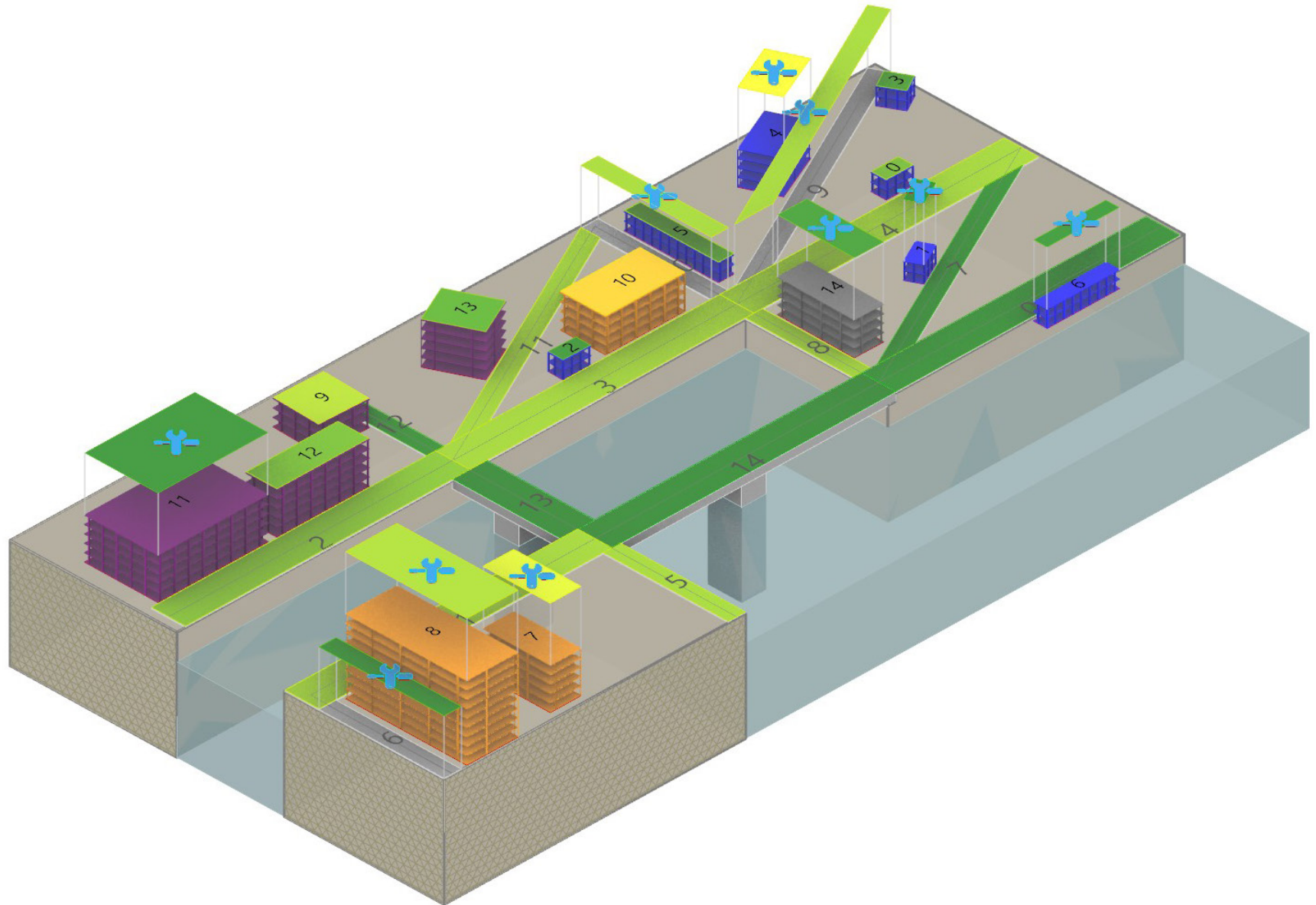
Quake Magnitude: 7.5 | CL: 283.76



# DCMAC

- Repair time = 0 days
- Repair time = 500 days

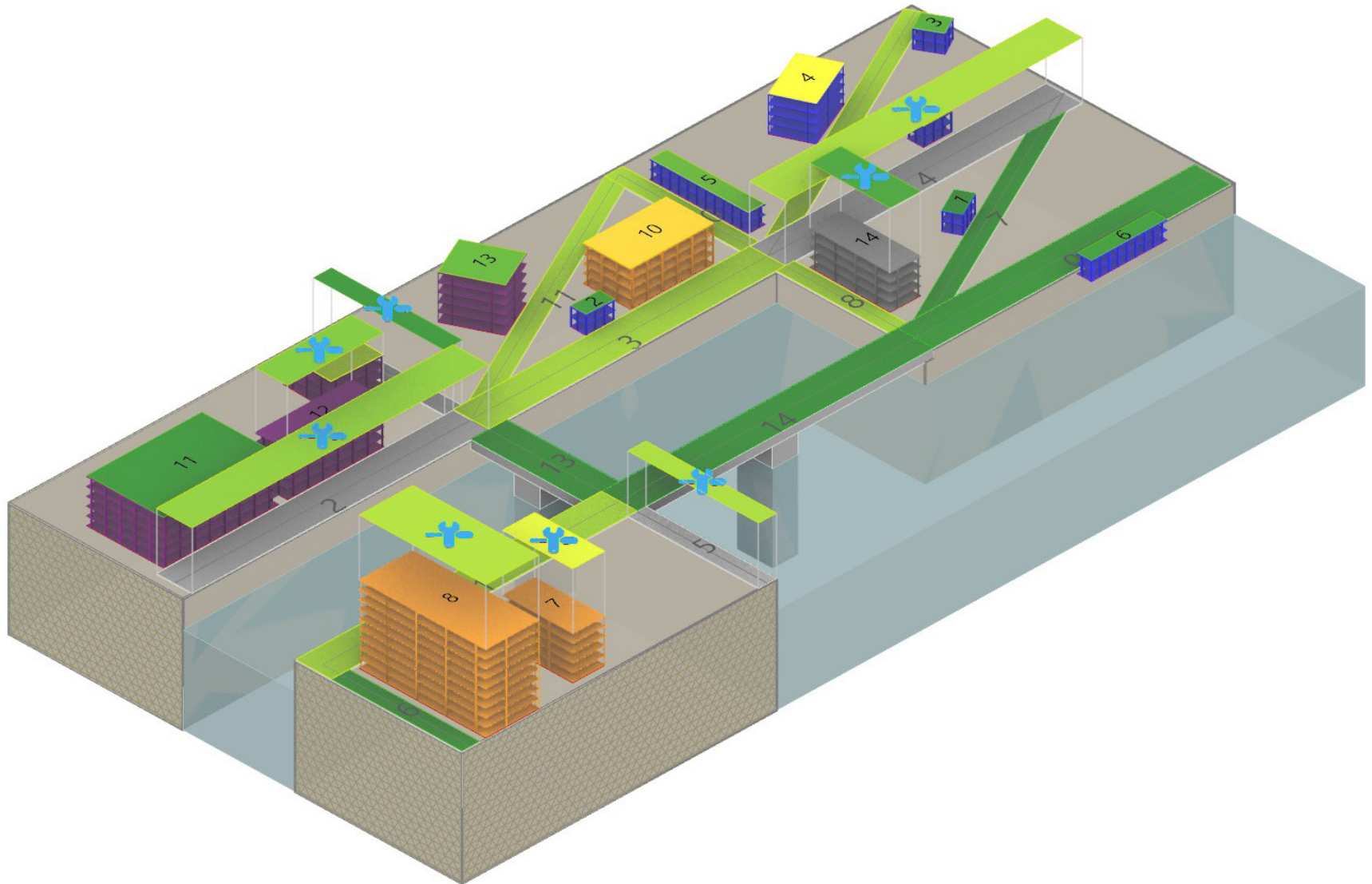
$t = 1$



# DCMAC

- Repair time = 0 days
- Repair time = 500 days

$t = 2$

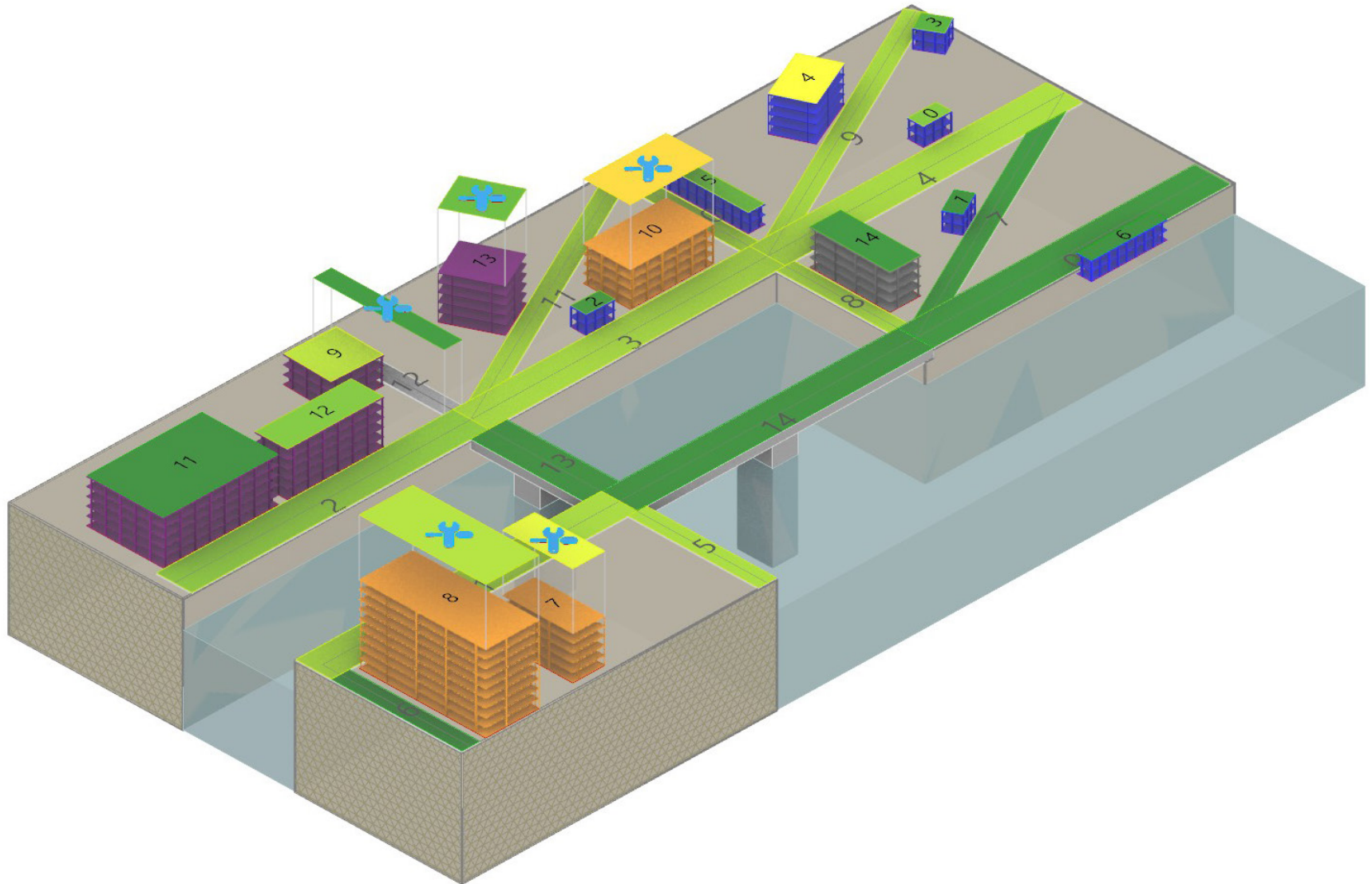




# DCMAC

- Repair time = 0 days
- Repair time = 500 days

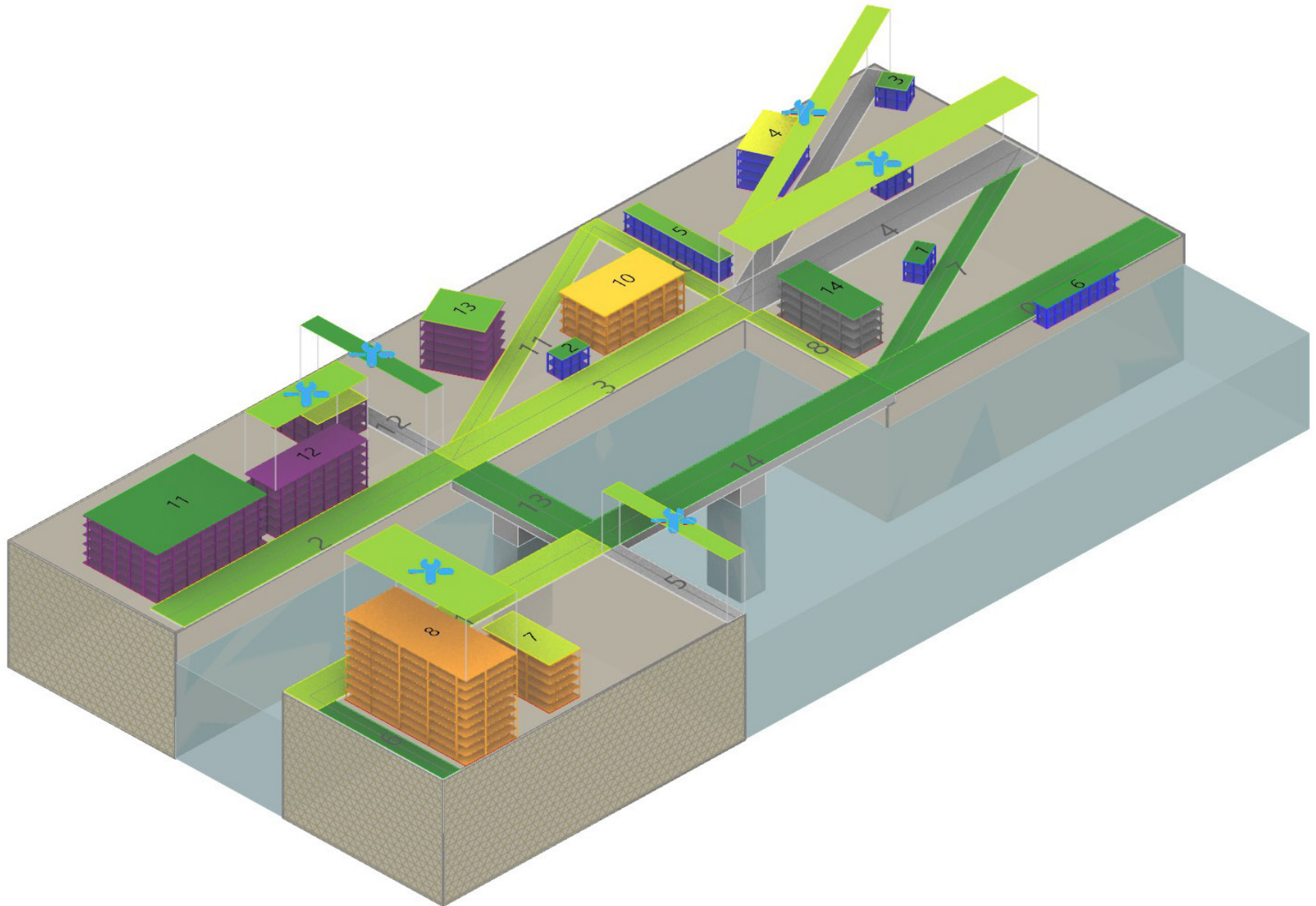
$t = 3$



# DCMAC

- Repair time = 0 days
- Repair time = 500 days

$t = 4$

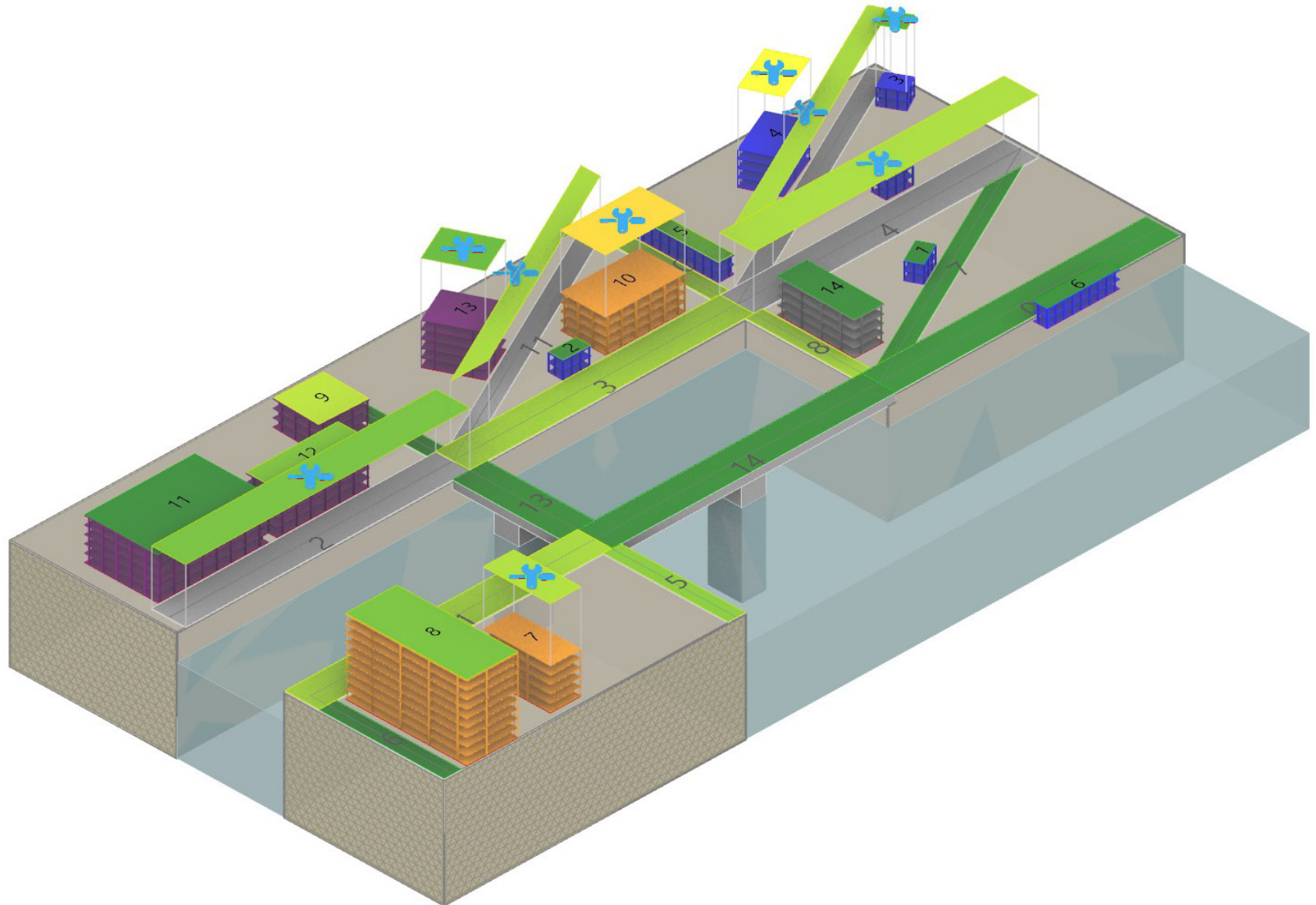




# DCMAC

- Repair time = 0 days
- Repair time = 500 days

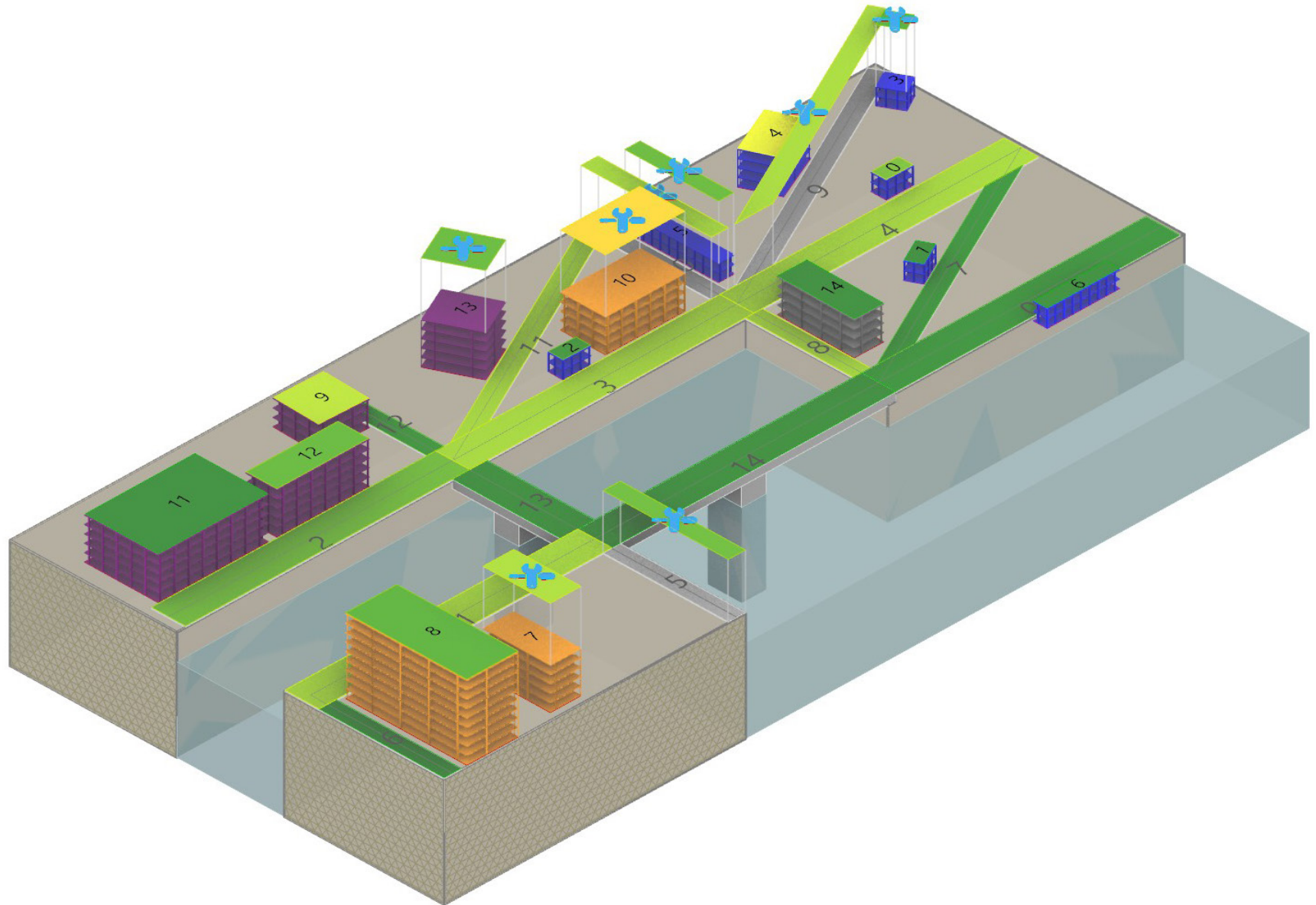
$t = 5$



# DCMAC

- Repair time = 0 days
- Repair time = 500 days

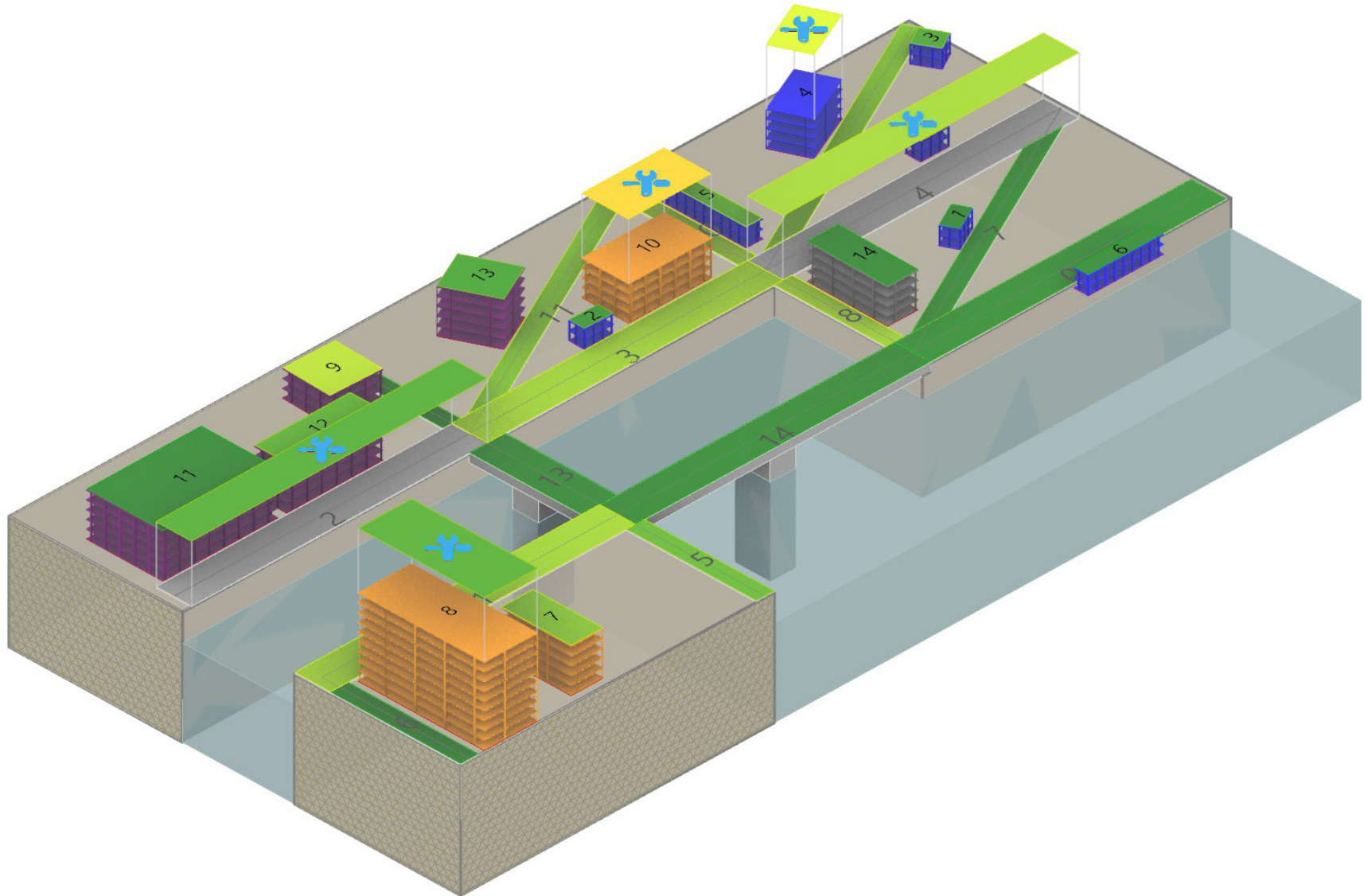
$t = 6$



# DCMAC

- Repair time = 0 days
- Repair time = 500 days

$t = 7$

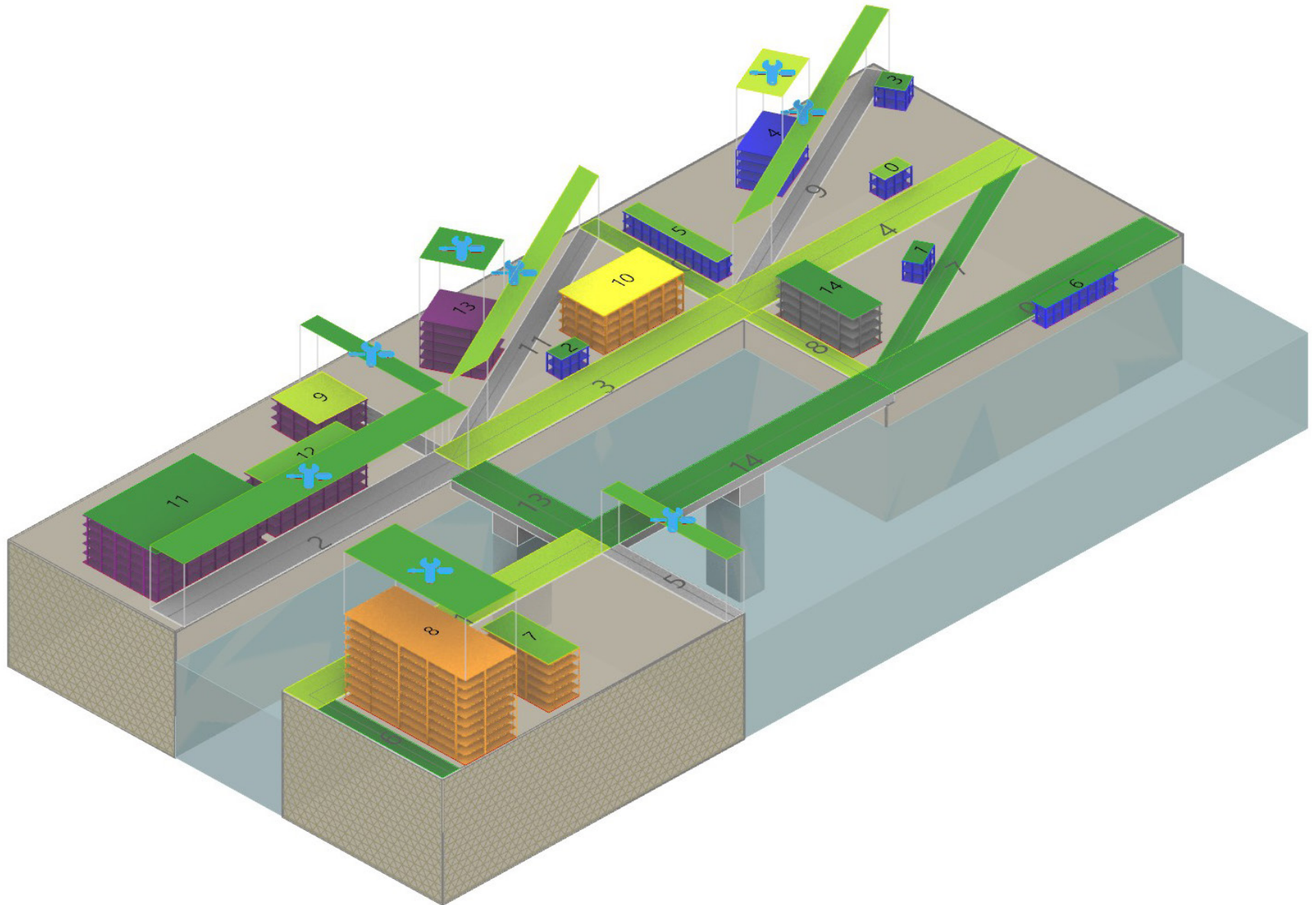




# DCMAC

- Repair time = 0 days
- Repair time = 500 days

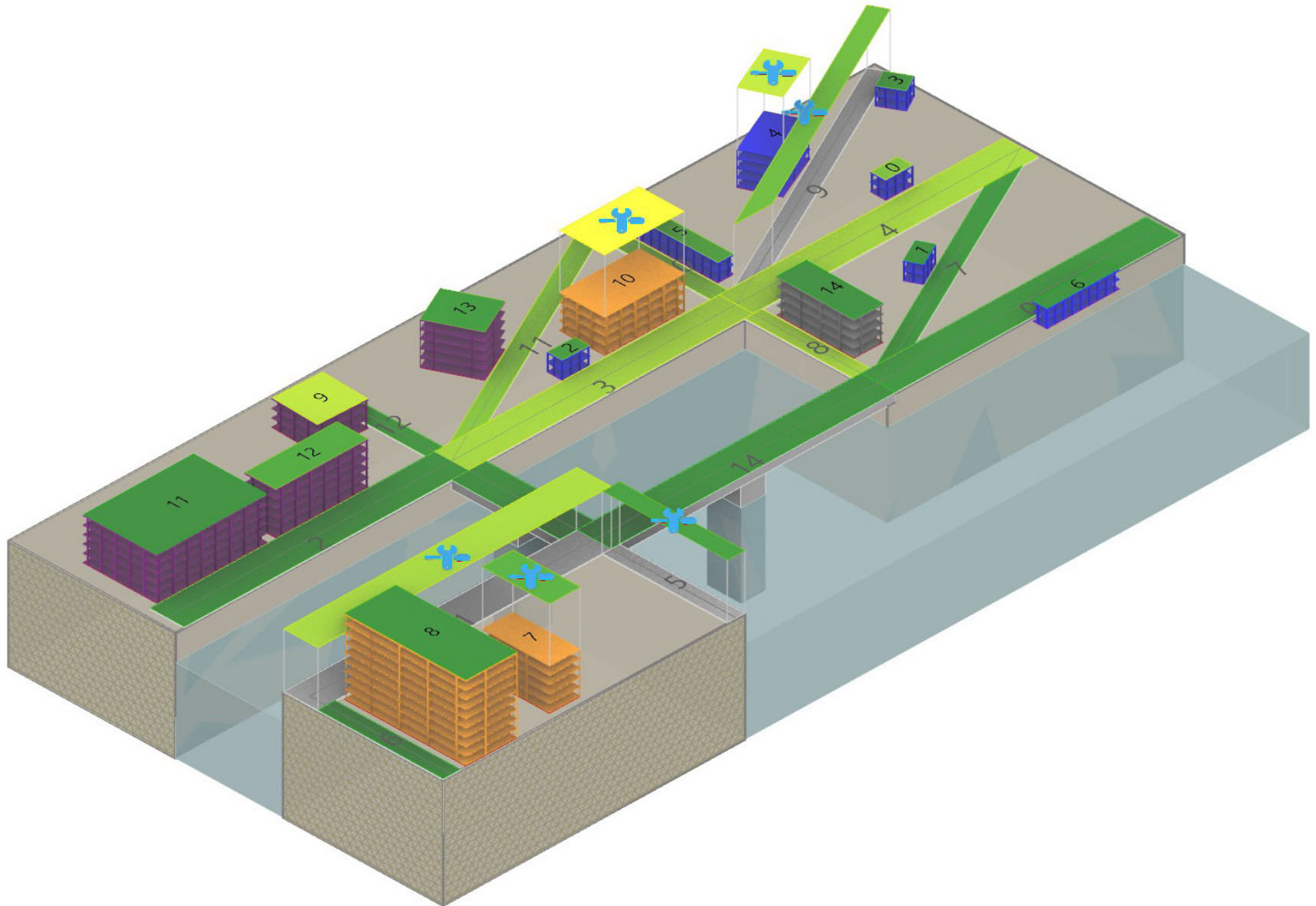
$t = 9$



# DCMAC

- Repair time = 0 days
- Repair time = 500 days

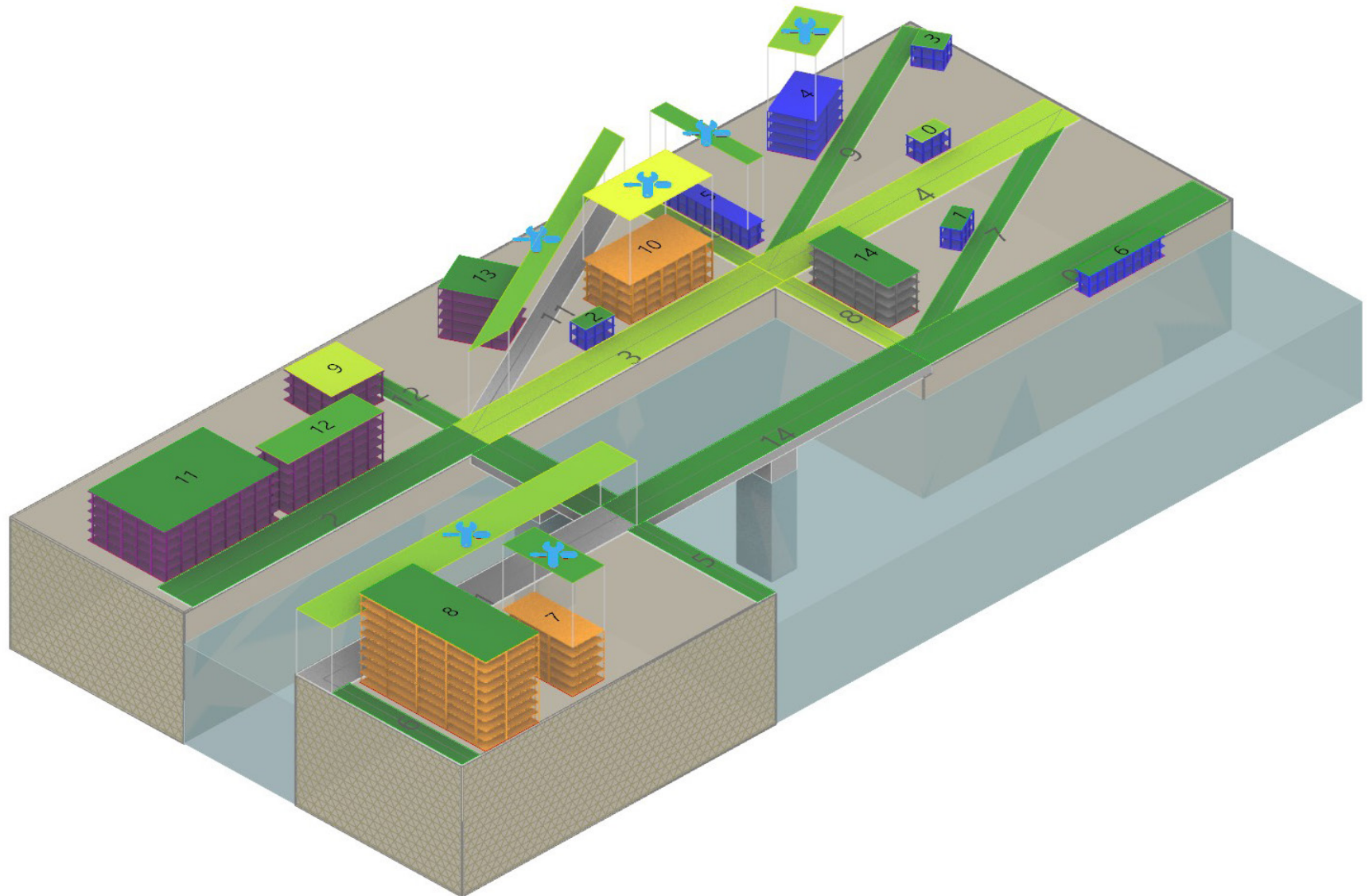
$t = 10$



# DCMAC

- Repair time = 0 days
- Repair time = 500 days

$t = 12$





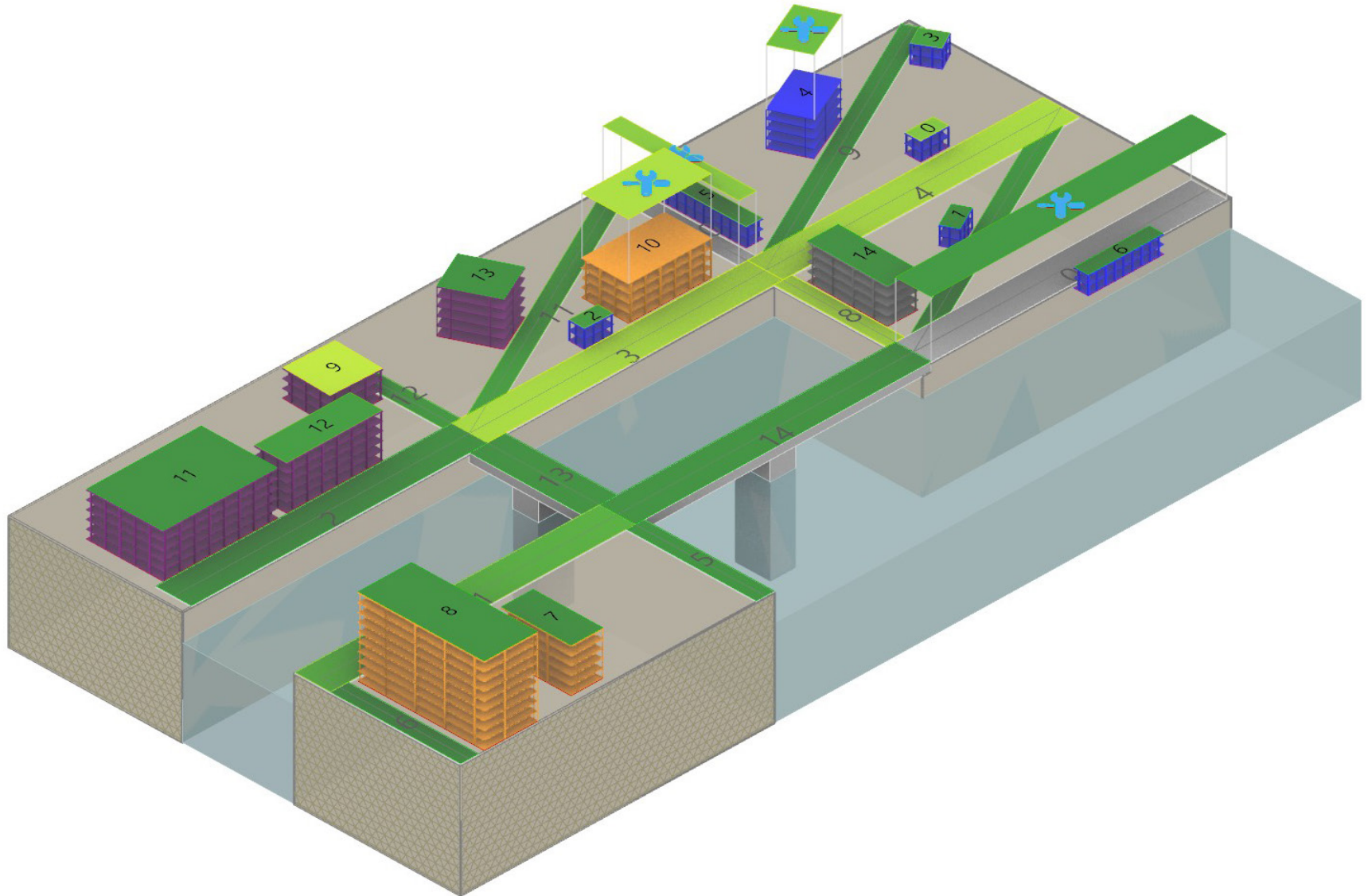
- Repair time = 0 days
- Repair time = 500 days

A 3D perspective view of a building layout, showing multiple levels and corridors. The layout is complex, with rooms and corridors numbered 1 through 14. The rooms are color-coded: green (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14), yellow (15), and blue (16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100). The corridors are green. The building is situated on a grey base, and the surrounding area is light blue.

# DCMAC

- Repair time = 0 days
- Repair time = 500 days

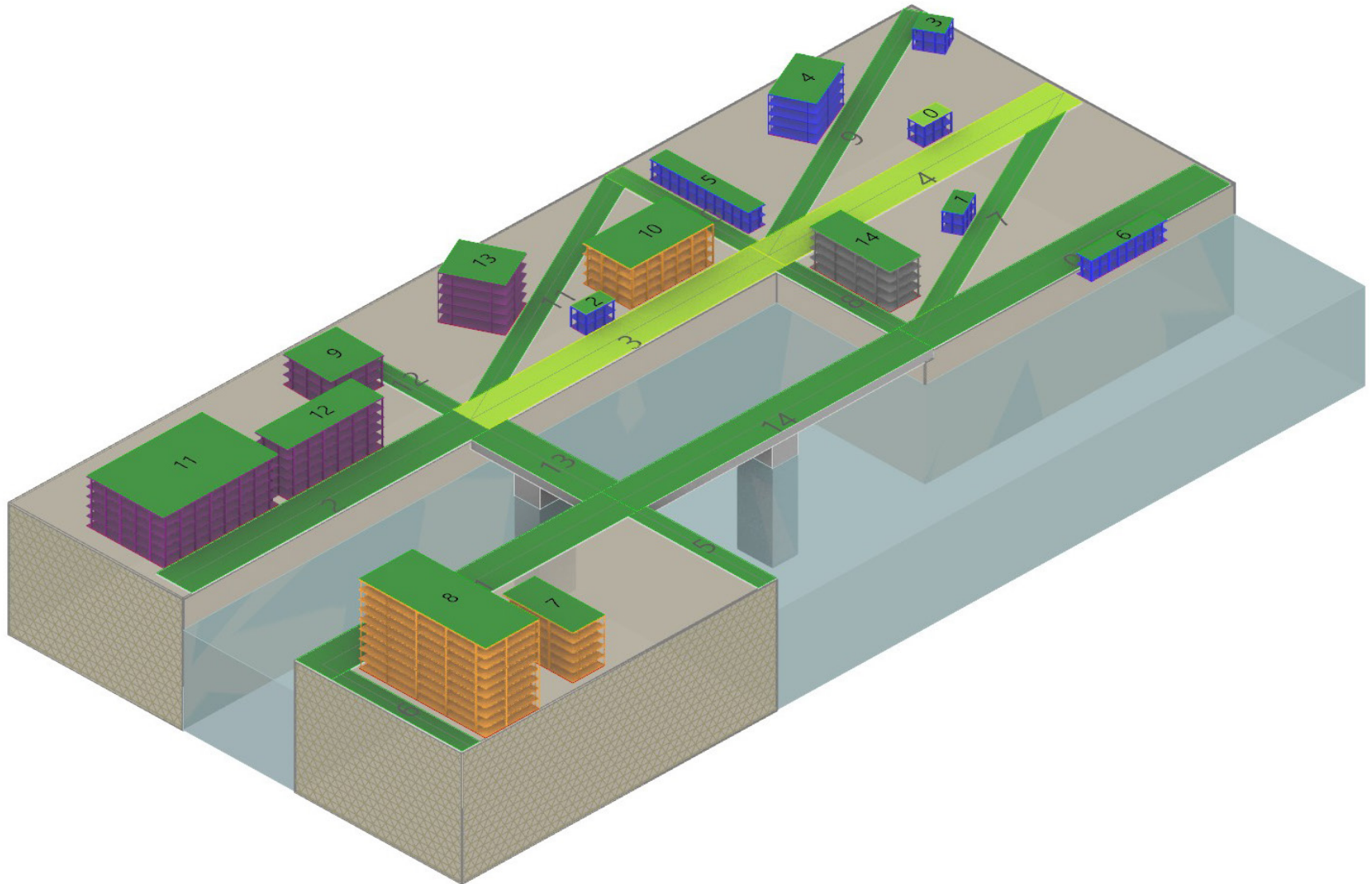
$t = 14$



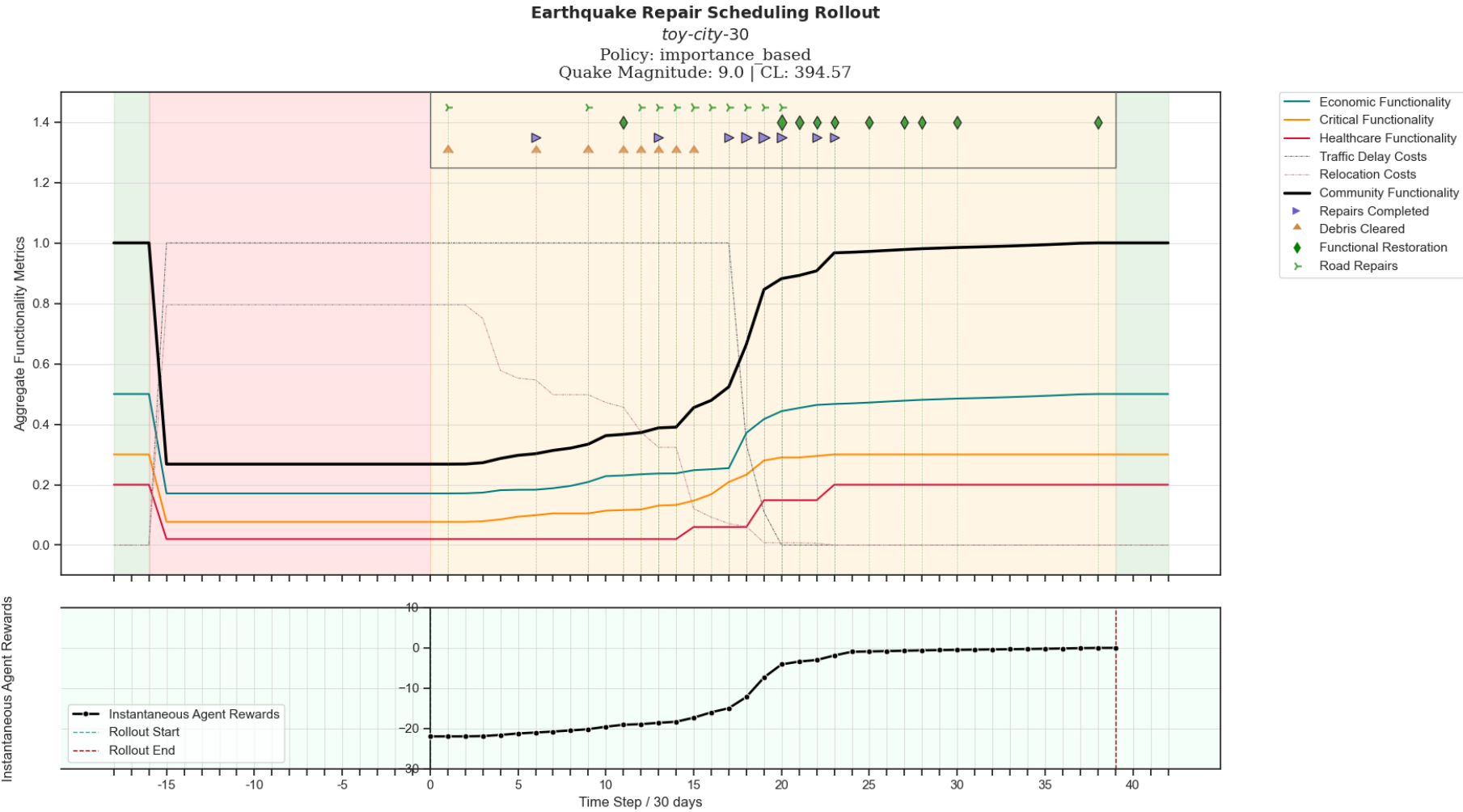
# DCMAC

- Repair time = 0 days
- Repair time = 500 days

$t = 100$



Importance Based (IMPB)

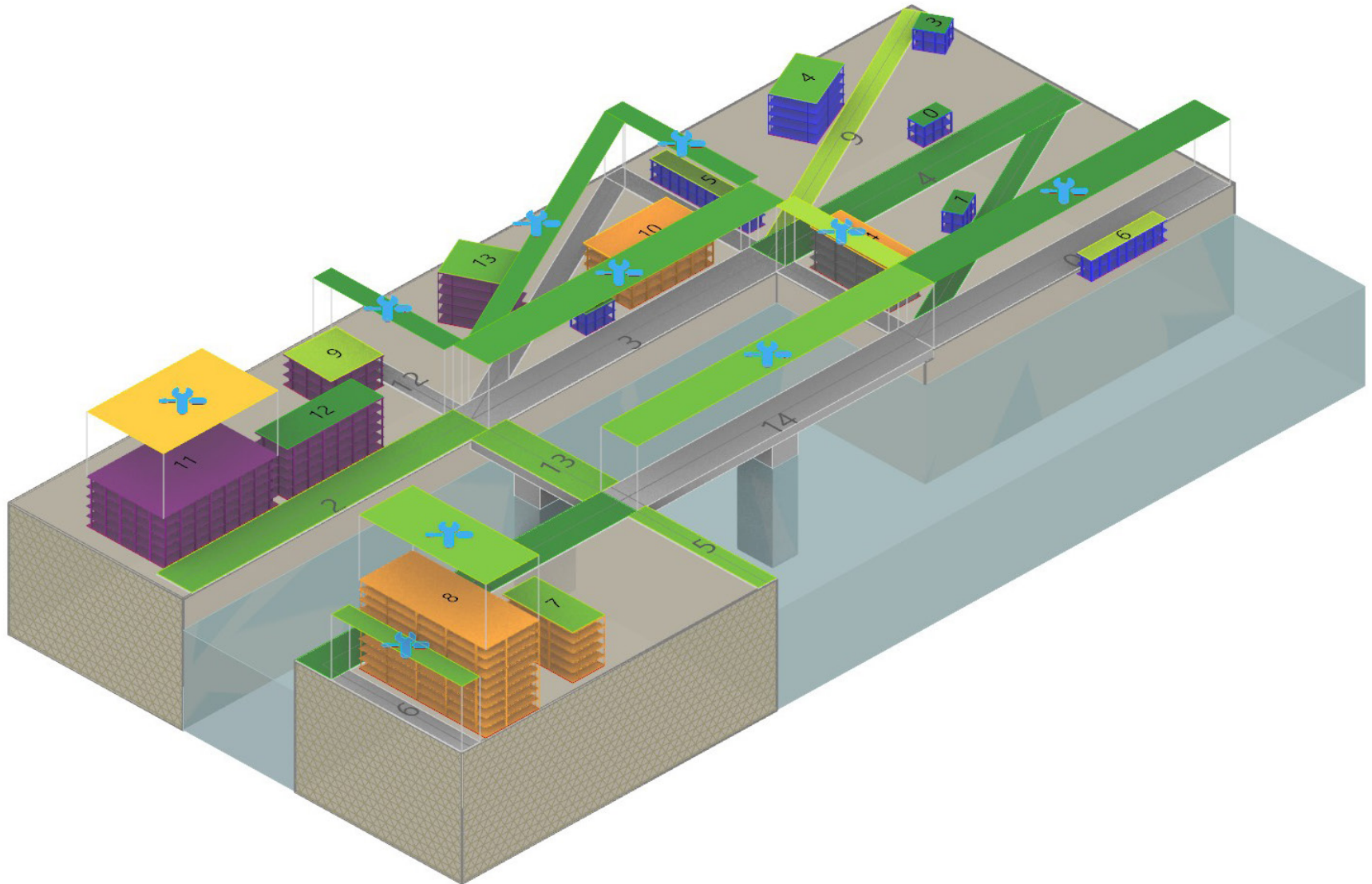




# IMPB

- Repair time = 0 days
- Repair time = 500 days

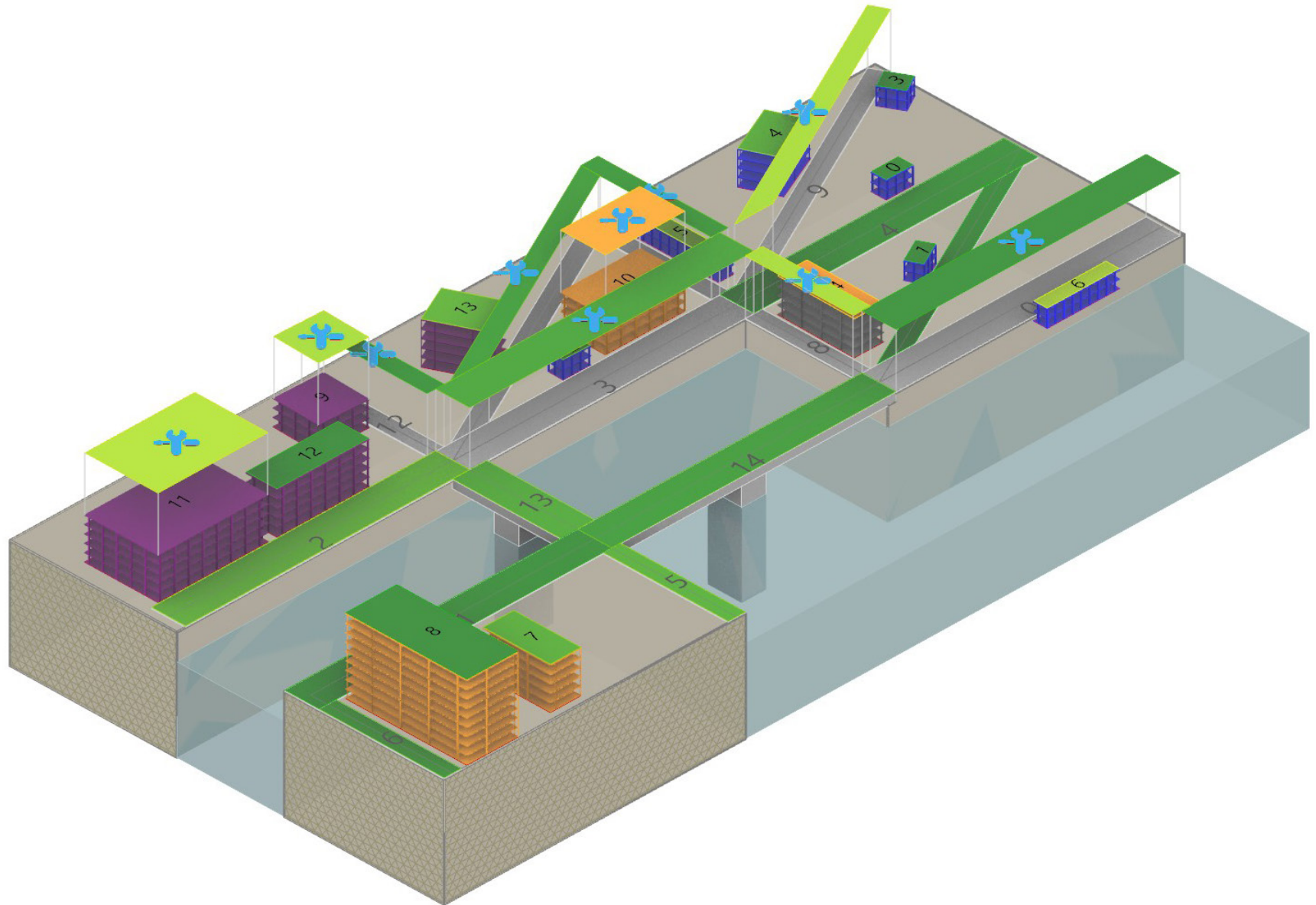
$t = 4$



# IMPB

- Repair time = 0 days
- Repair time = 500 days

$t = 9$

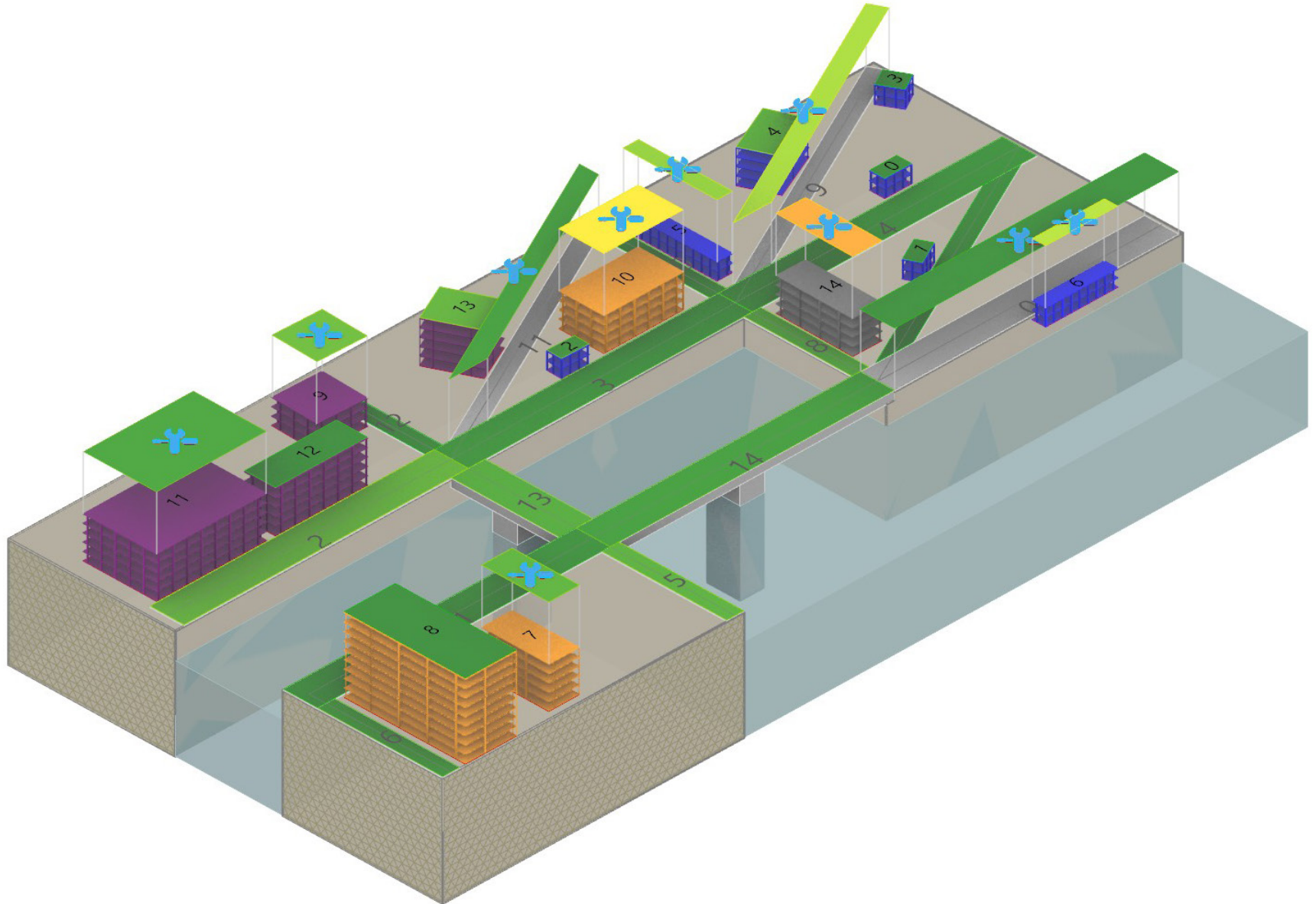




# IMPB

- Repair time = 0 days
- Repair time = 500 days

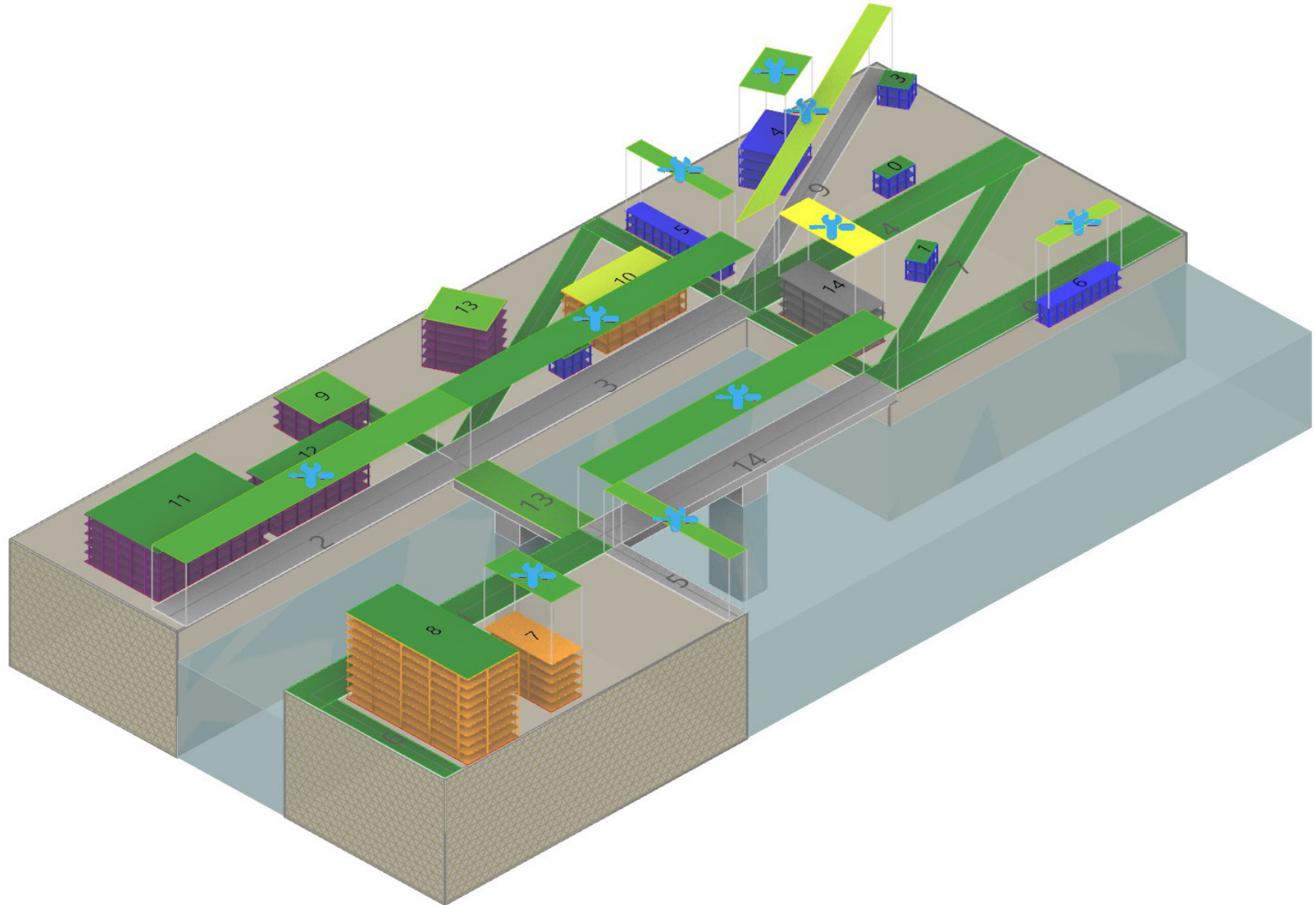
$t = 13$



# IMPB

- Repair time = 0 days
- Repair time = 500 days

t = 16



## *Conclusions*



## Work Presented

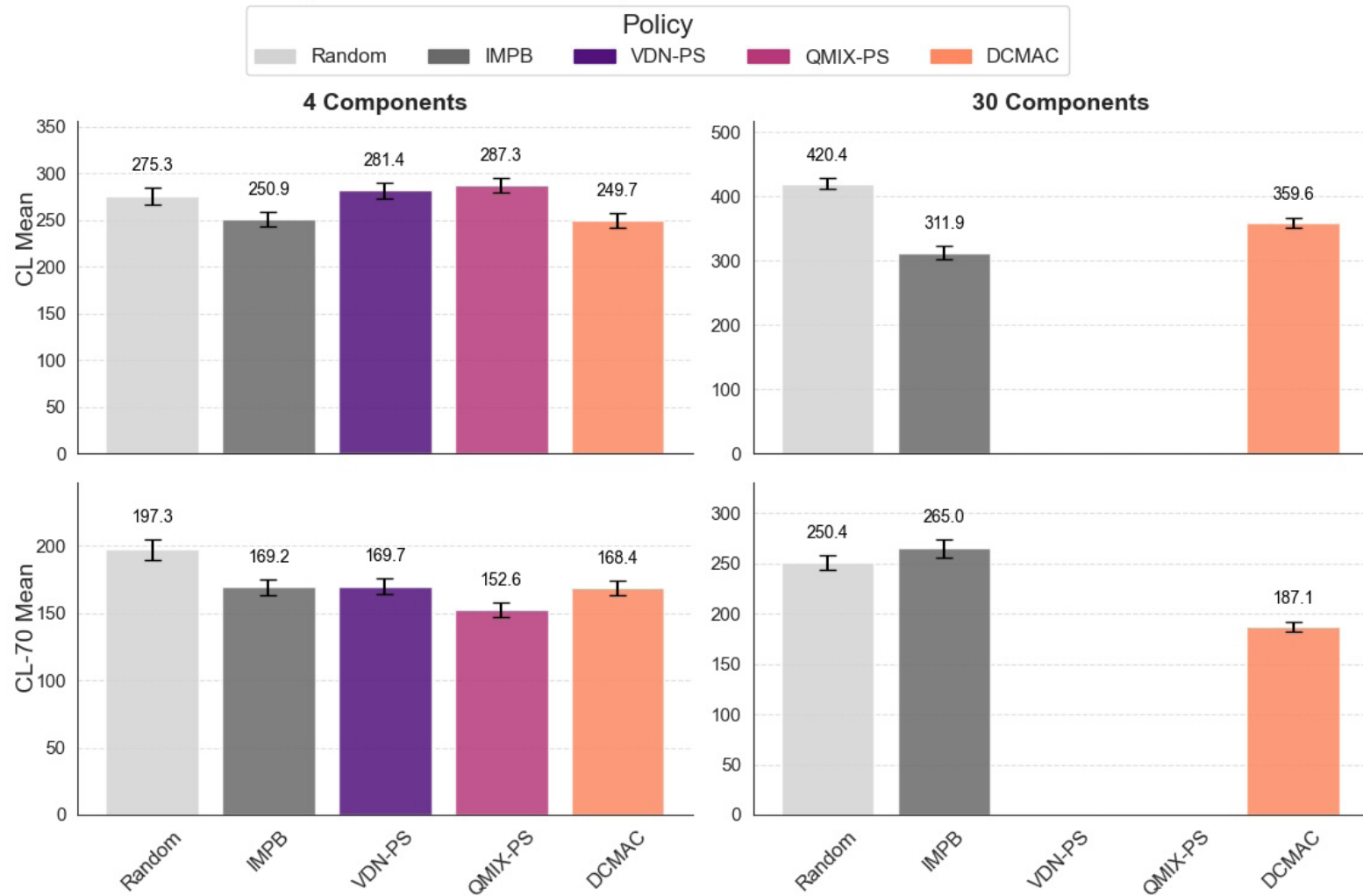
Two environments are modelled (4 components, 30 components)

Stochastic earthquake scenario set

Stochastic fragility and vulnerability functions

Importance based repair scheduling is compared to DRL

### Policy Performance Comparison Across Environments



## Key Takeaways

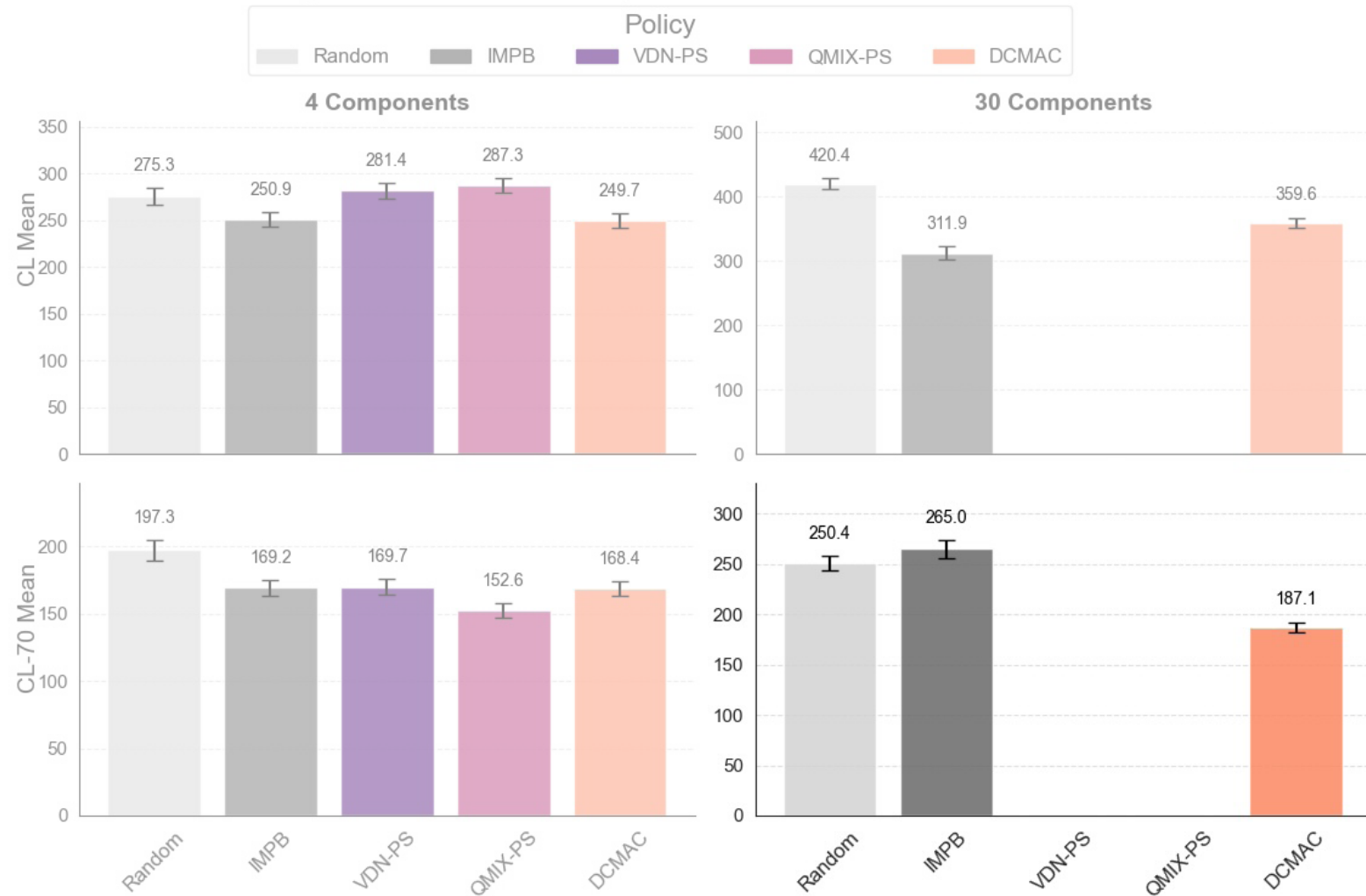
*DRL performs better in the early recovery phase (effective early prioritisation)*

*IMPB performs better in full recovery (poor early prioritisation)*

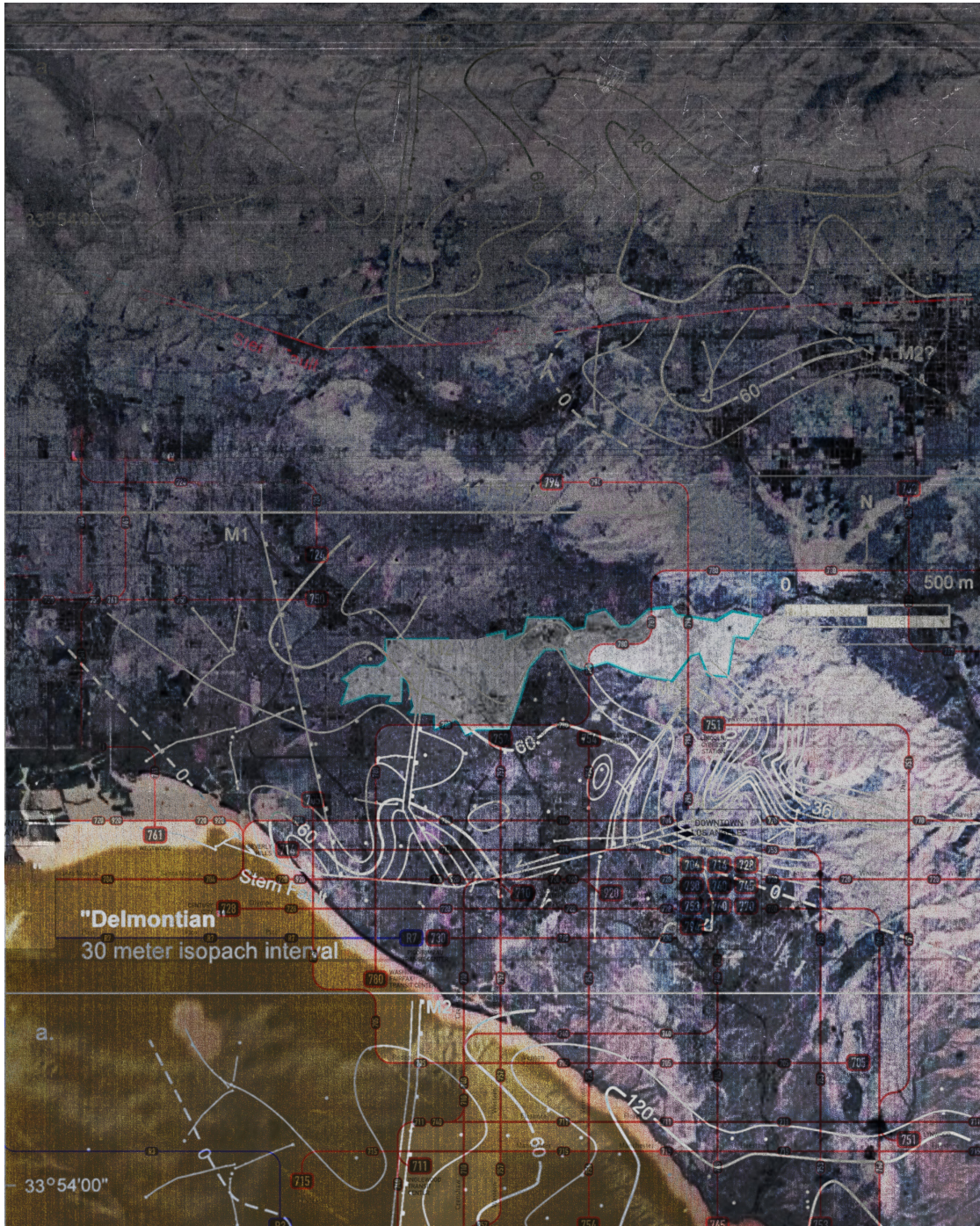
*DRL is resource-hungry, requiring approx. 40 hrs of training*

*DRL performs better for environments with more, complex interdependencies*

## Policy Performance Comparison Across Environments







# Q-RES MARL

*A Resilience-Based MARL Framework for the Post-Earthquake Recovery of Interdependent Infrastructures*

Antonios Mavrotas - AR3B05 - P5 Presentation - 23/06/2025

*Mentors: Charalampos Andriotis and Simona Bianchi  
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