Q-RES MARL

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

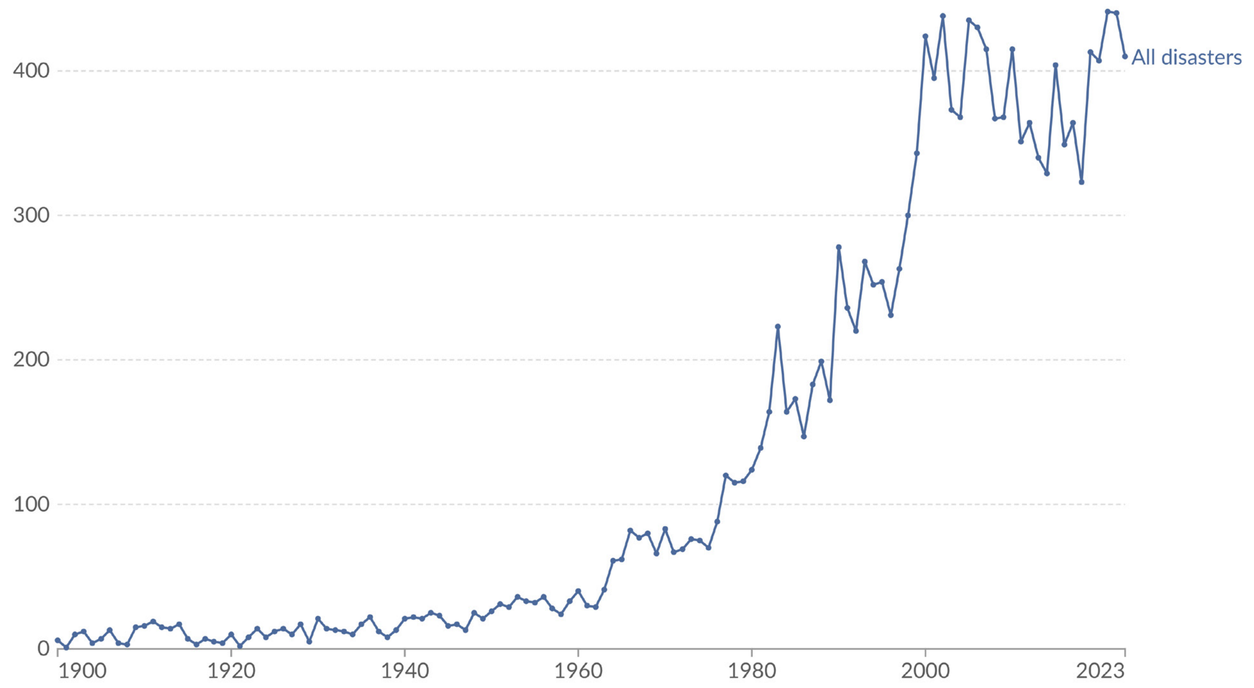
Antonios Mavrotas - AR3B05 - P5 Presentation - 23/06/2025

Mentors: Charalampos Andriotis and Simona Bianchi

Invaluable assistance was also provided by Prateek Bhustali

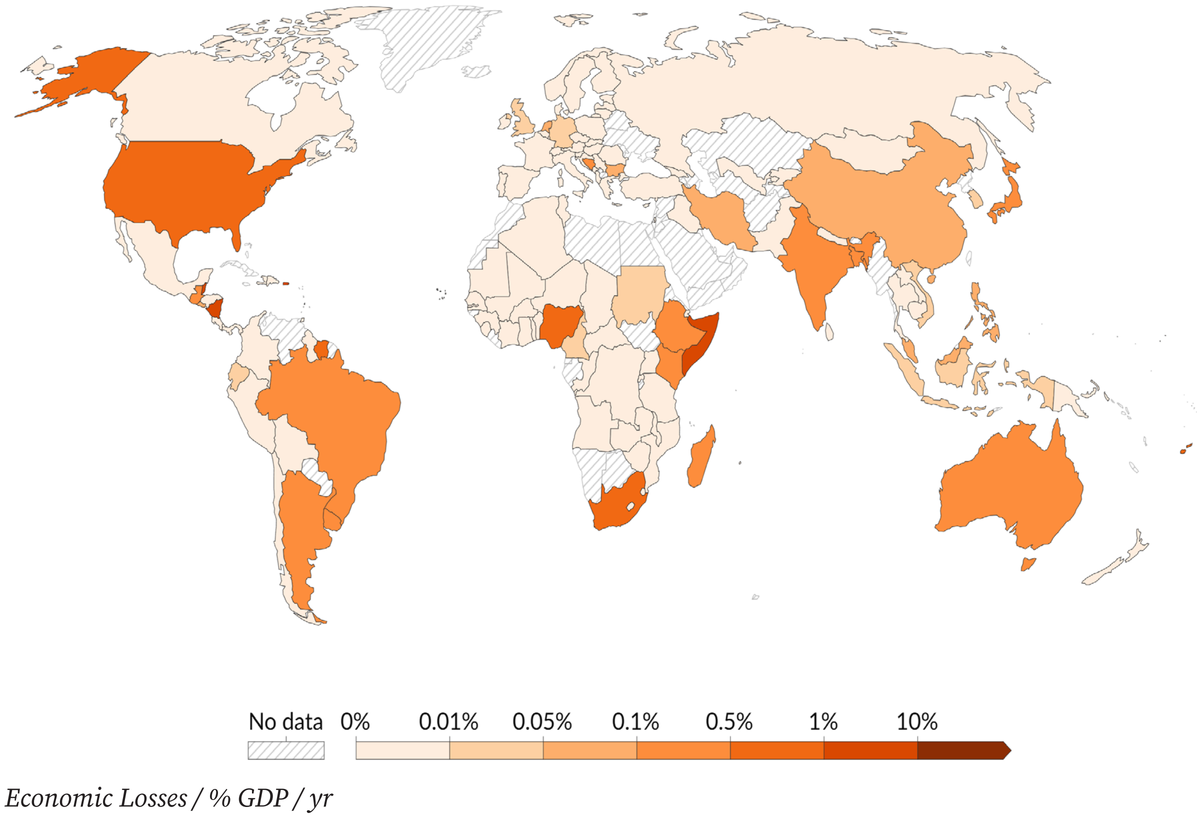
Natural Disasters: Wider Urban Impacts on Built Environment

Increasing Disaster Frequency

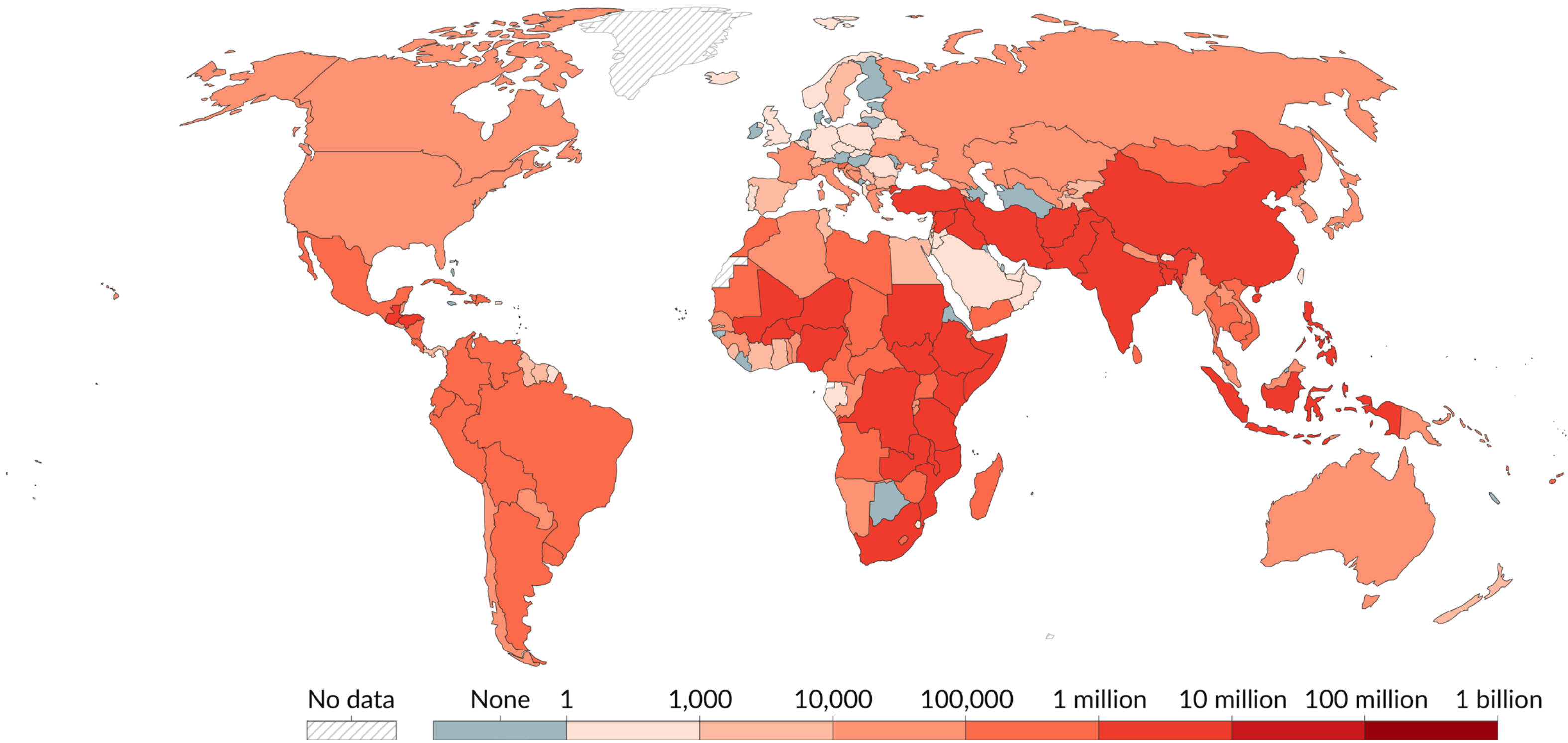


Disaster Frequency / #

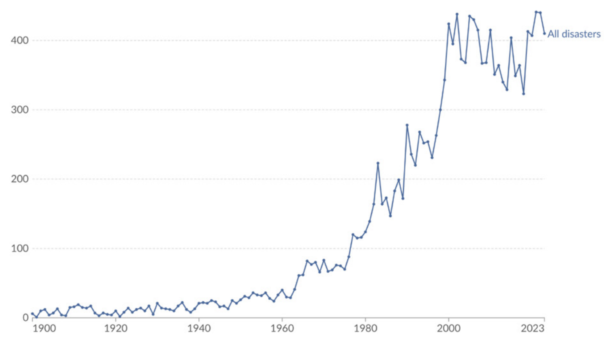
Significant Economic Shocks

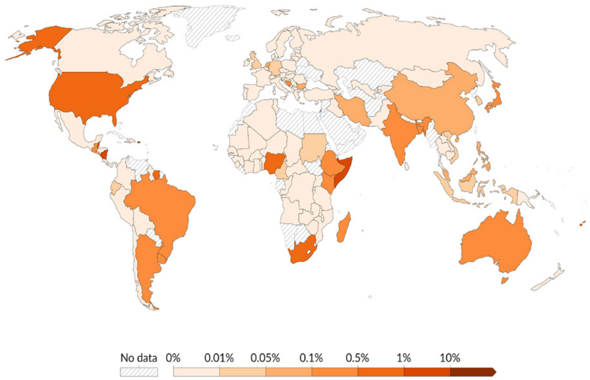


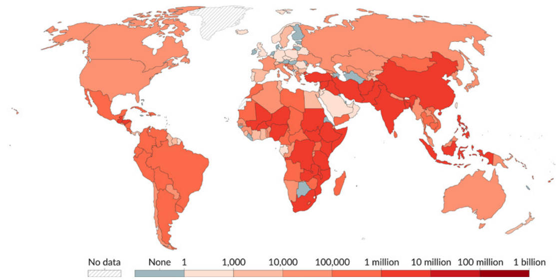
Exceeding Human Losses



 # people req. assistance (2019)

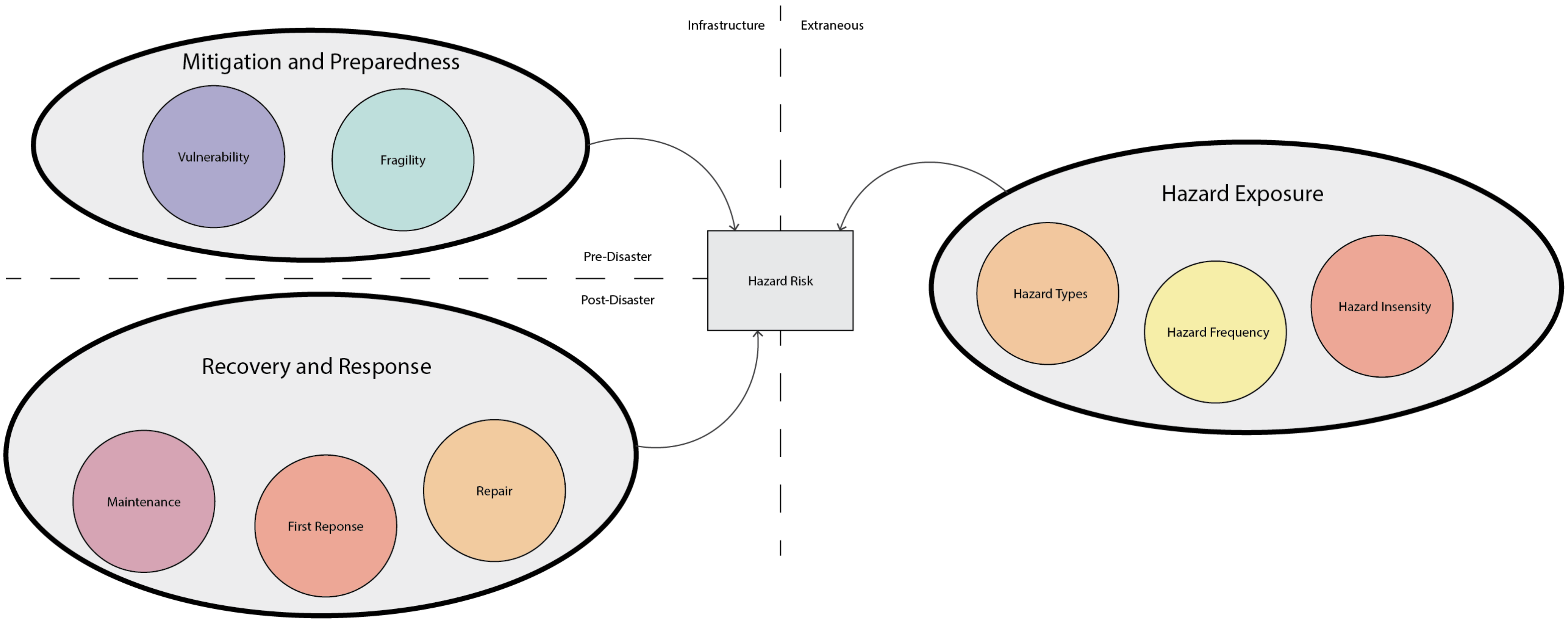




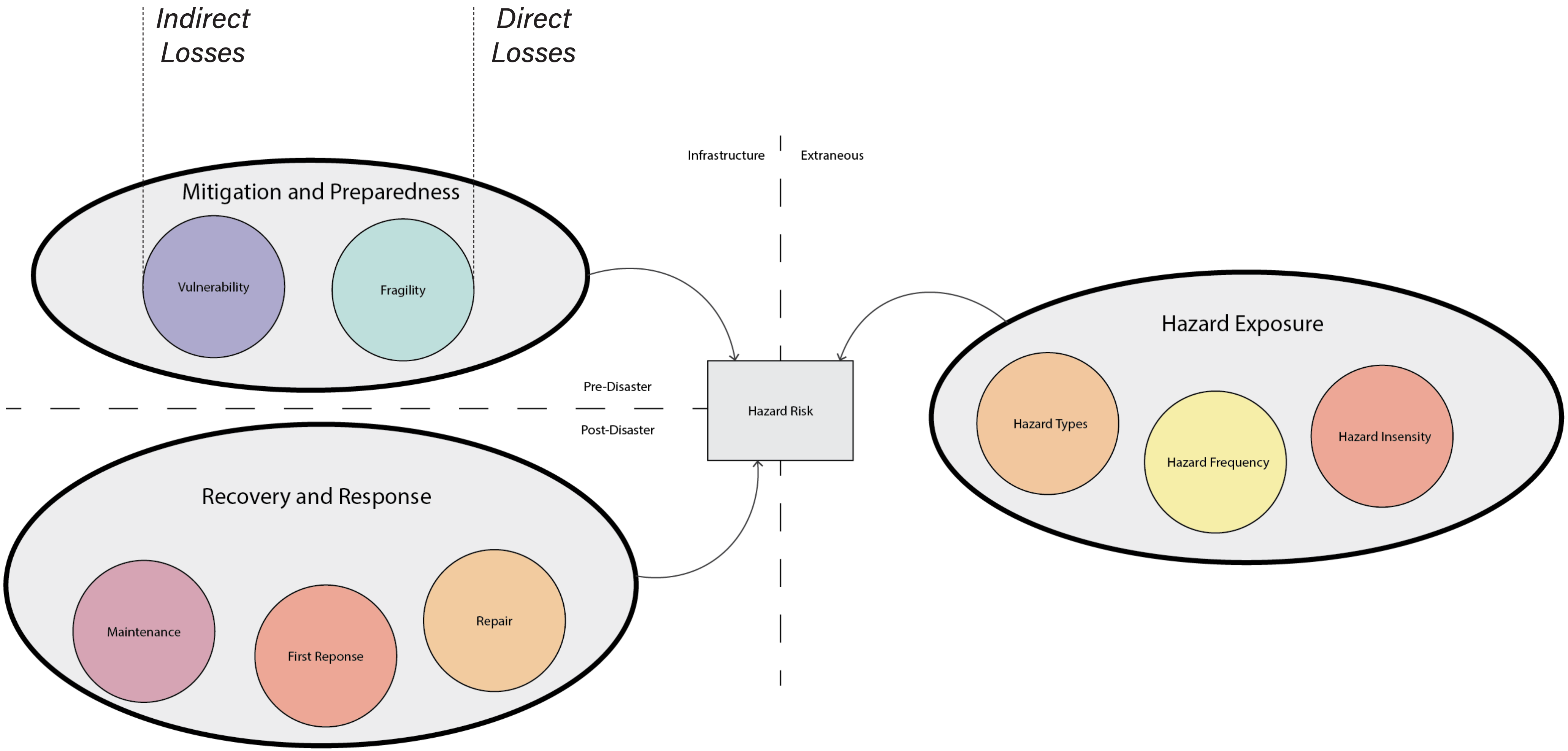


Increased Global Hazard Risk

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

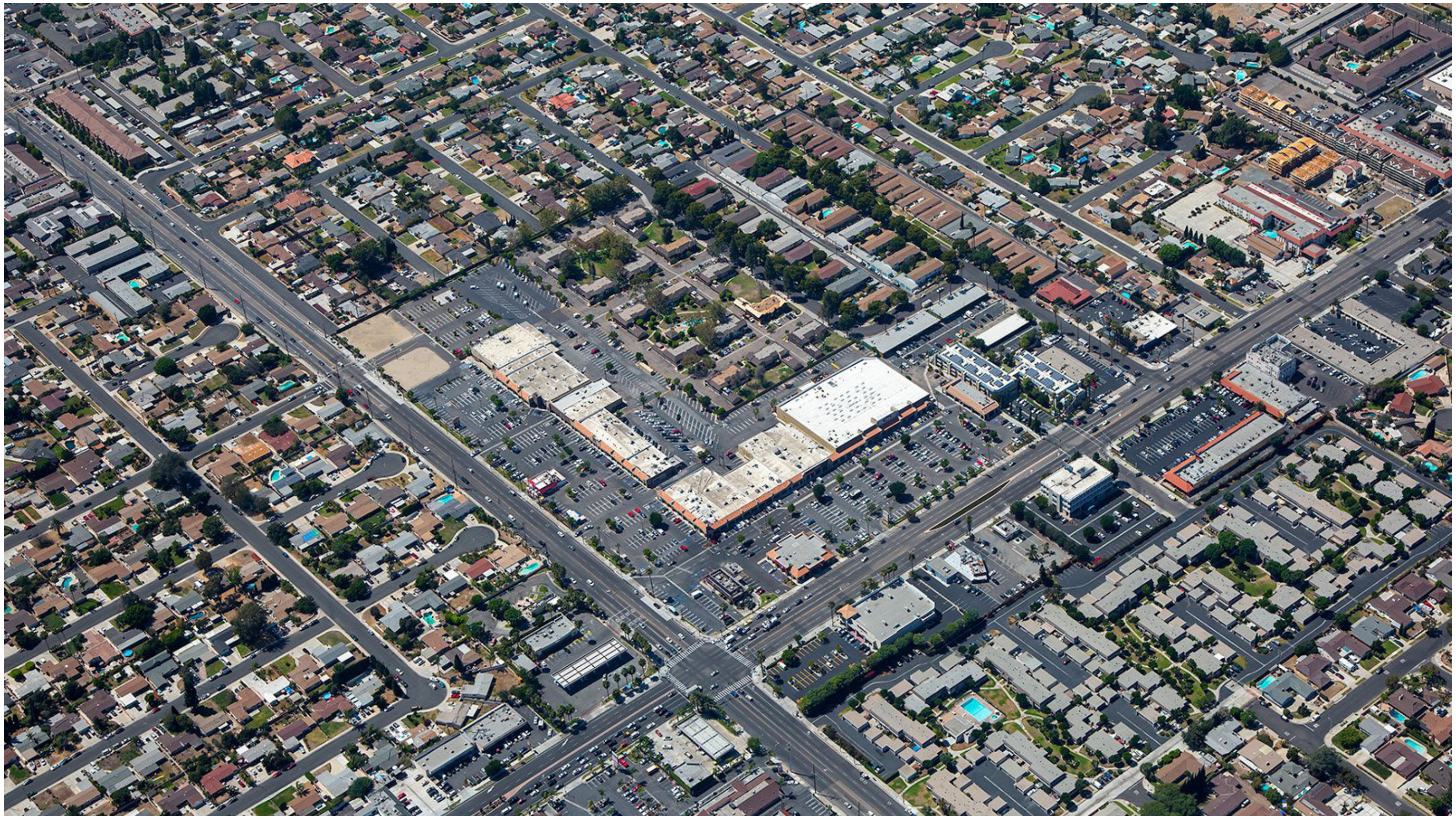
Transportation Network → *Building Portfolio*

Road Capacity is Dependent on Building Debris

2023 Inskenderun Earthquake, Turkey

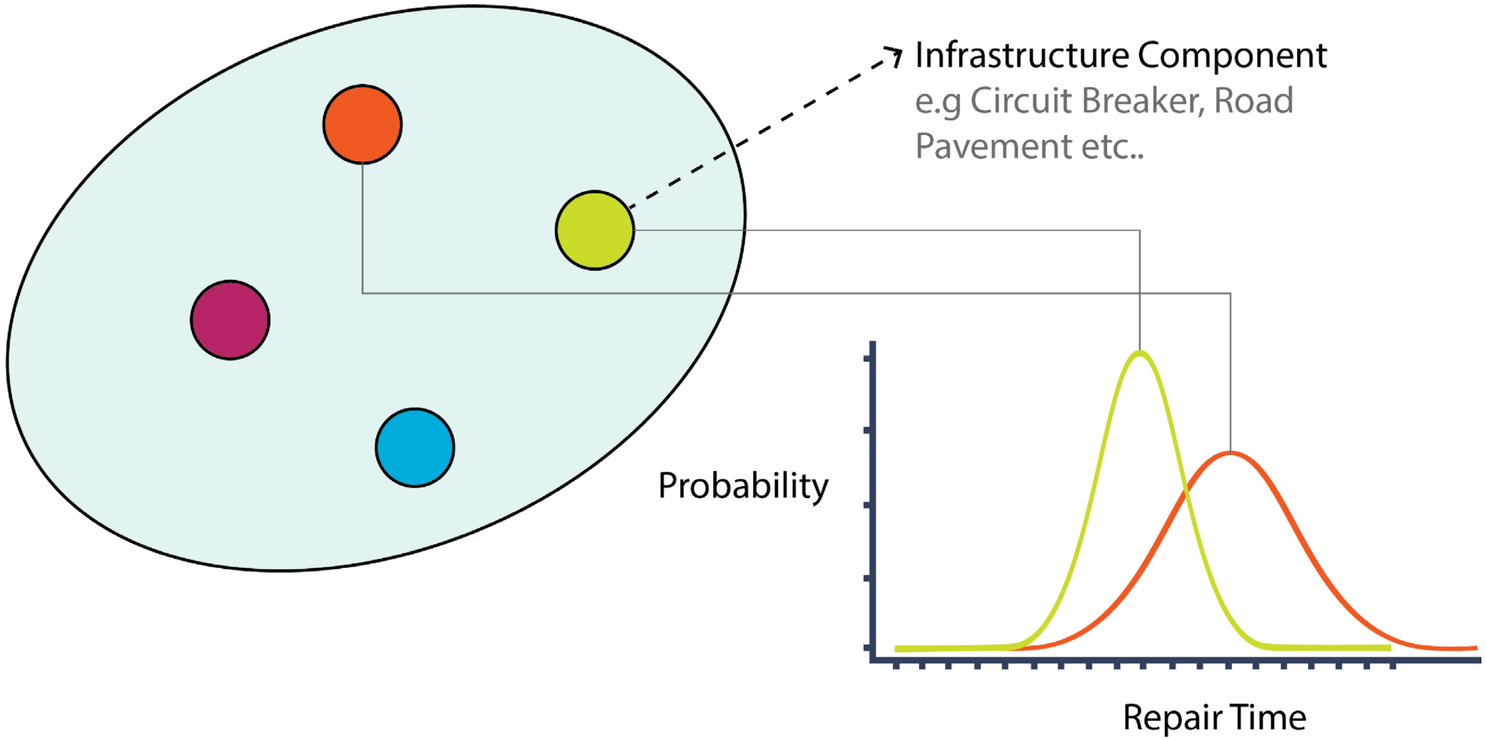
How Can We Predict Damage To Infrastructure?

Large Scale Damage Prediction

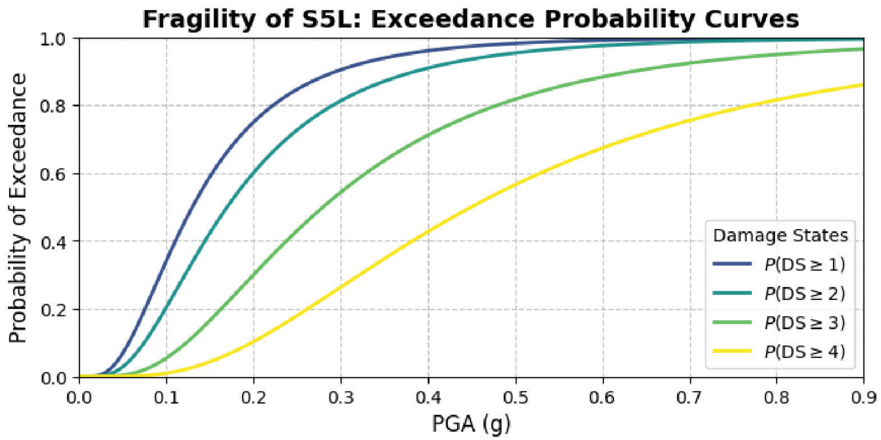


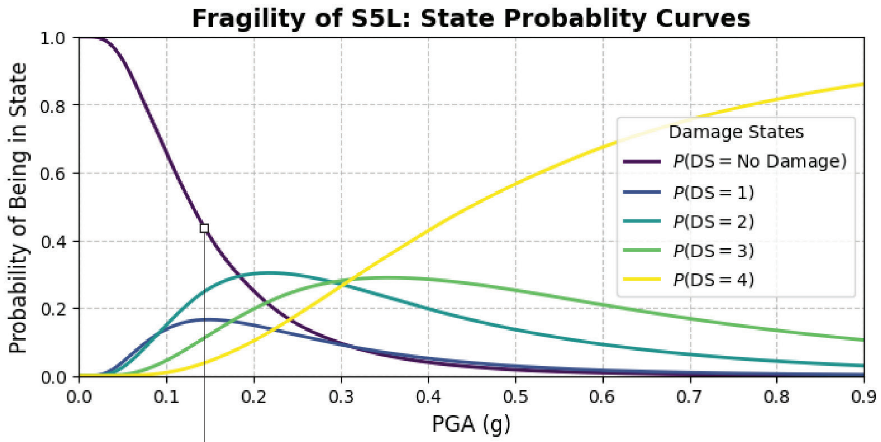
Infrastructure in Anaheim, US.

Stochastic Damage Prediction



Fragility Curves





No visible

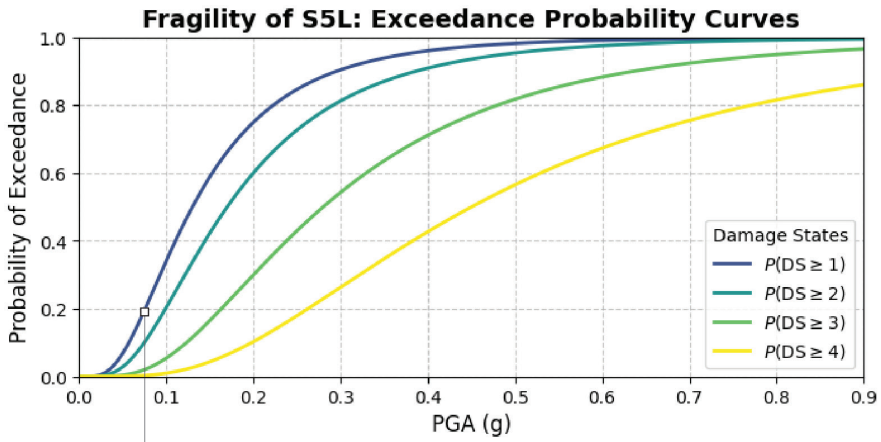
Minor

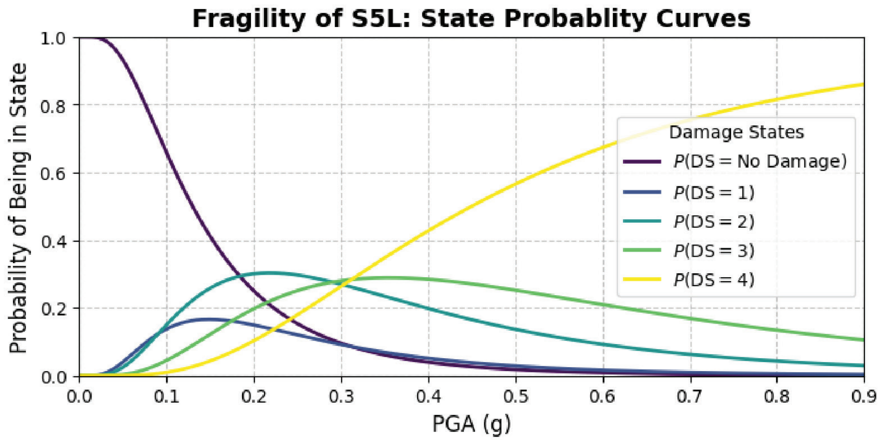
Moderate

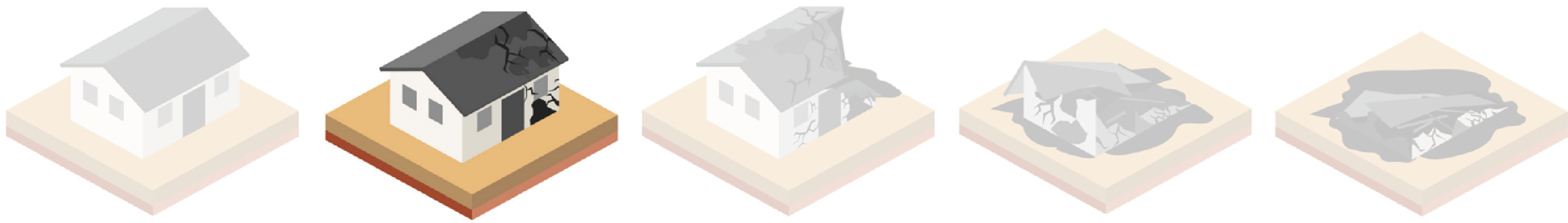
Major

Complete destruction

Fragility Curves







No visible

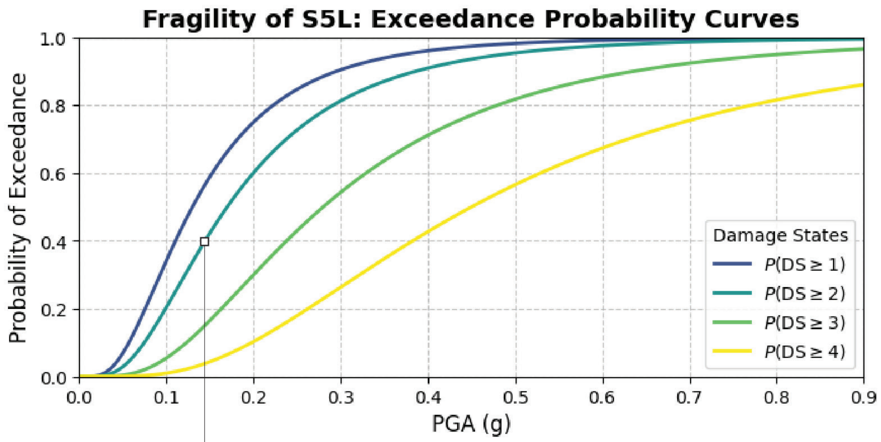
Minor

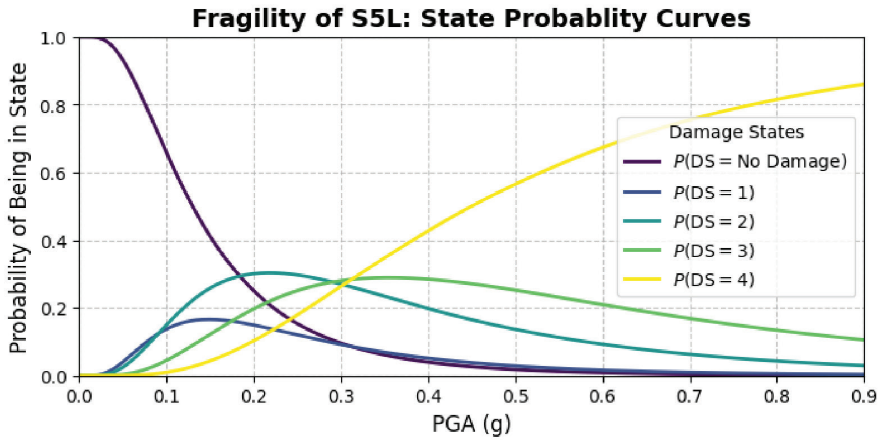
Moderate

Major

Complete destruction

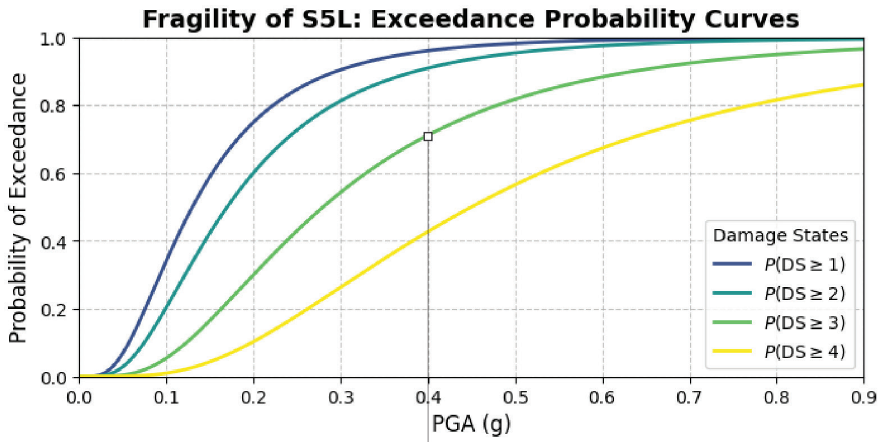
Fragility Curves

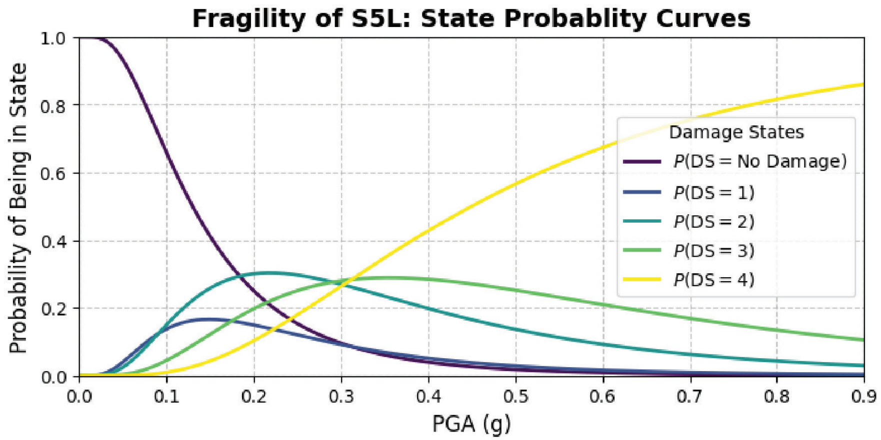




No visible | Minor | **Moderate** | Major | Complete destruction

Fragility Curves





No visible

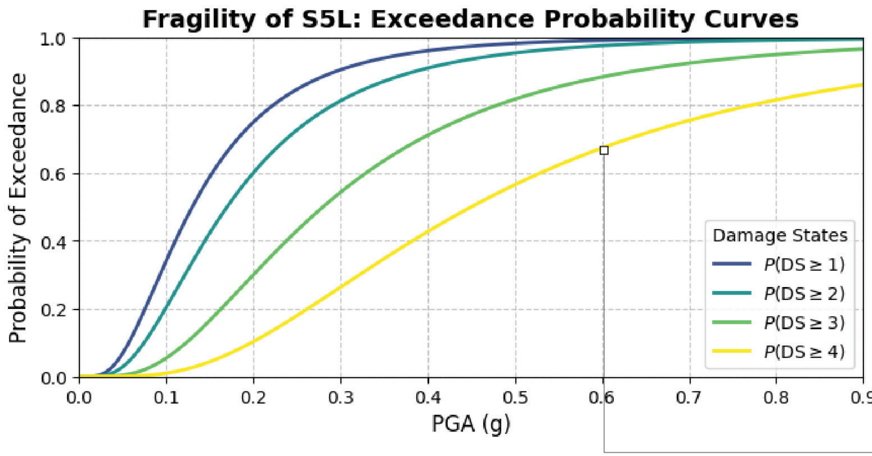
Minor

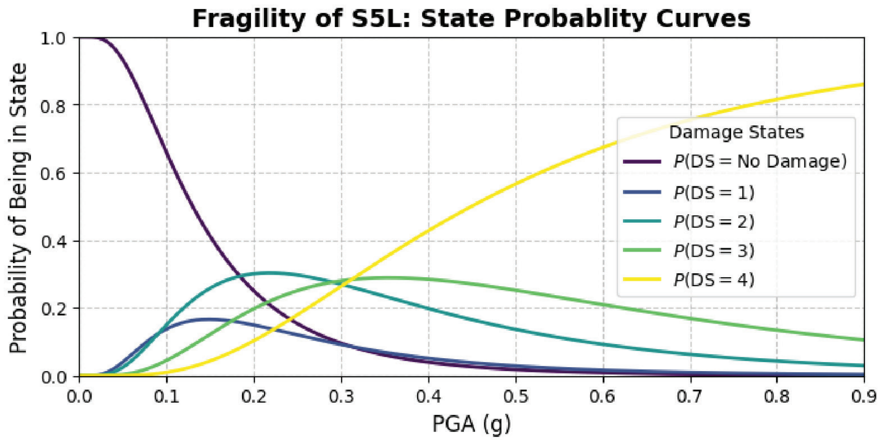
Moderate

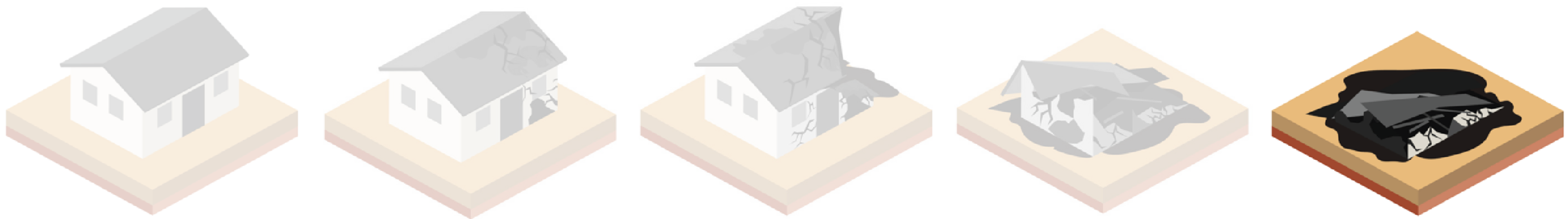
Major

Complete destruction

Fragility Curves







No visible

Minor

Moderate

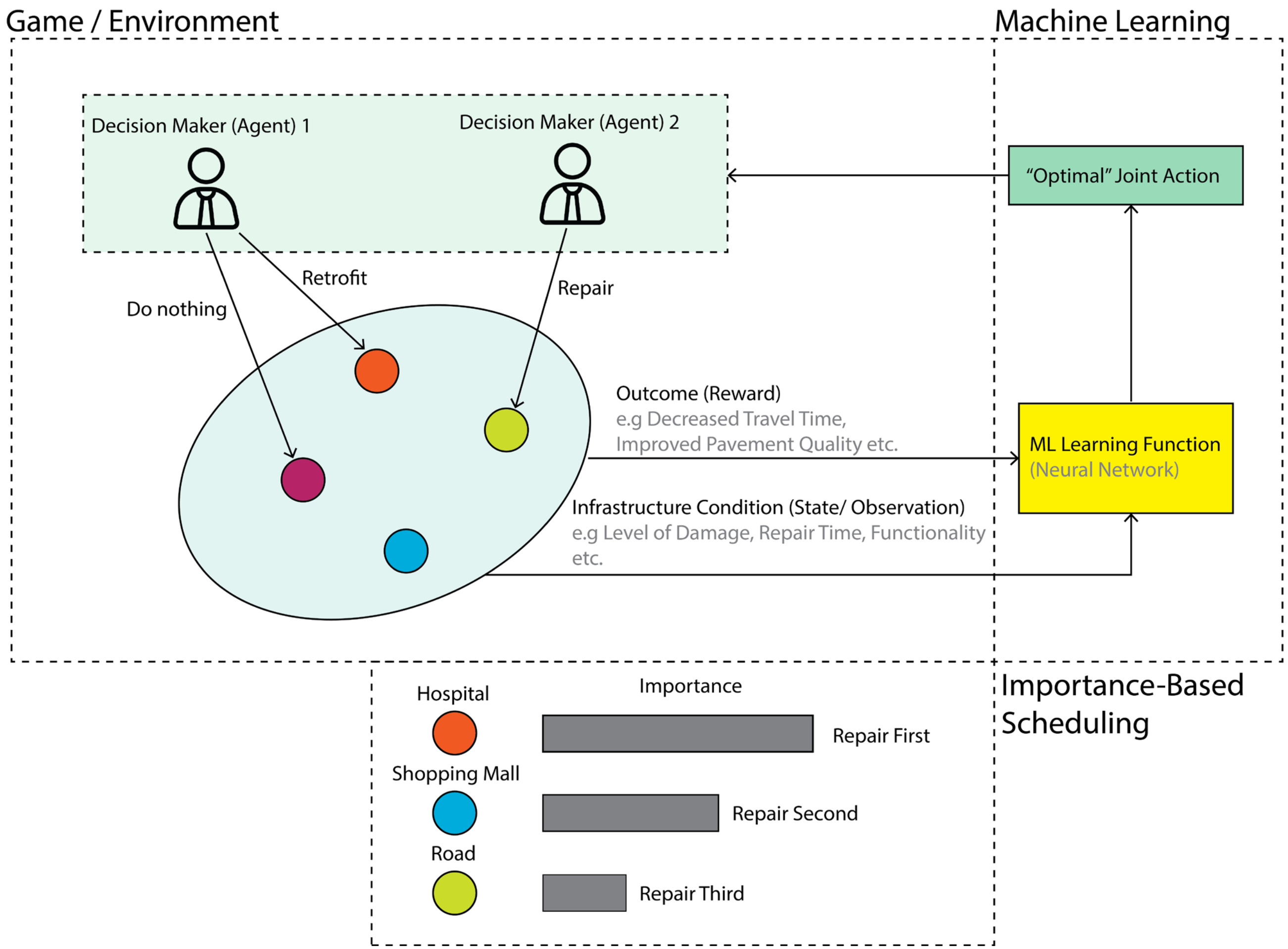
Major

Complete destruction

Devising Optimal Repair Strategies

Hypothesis

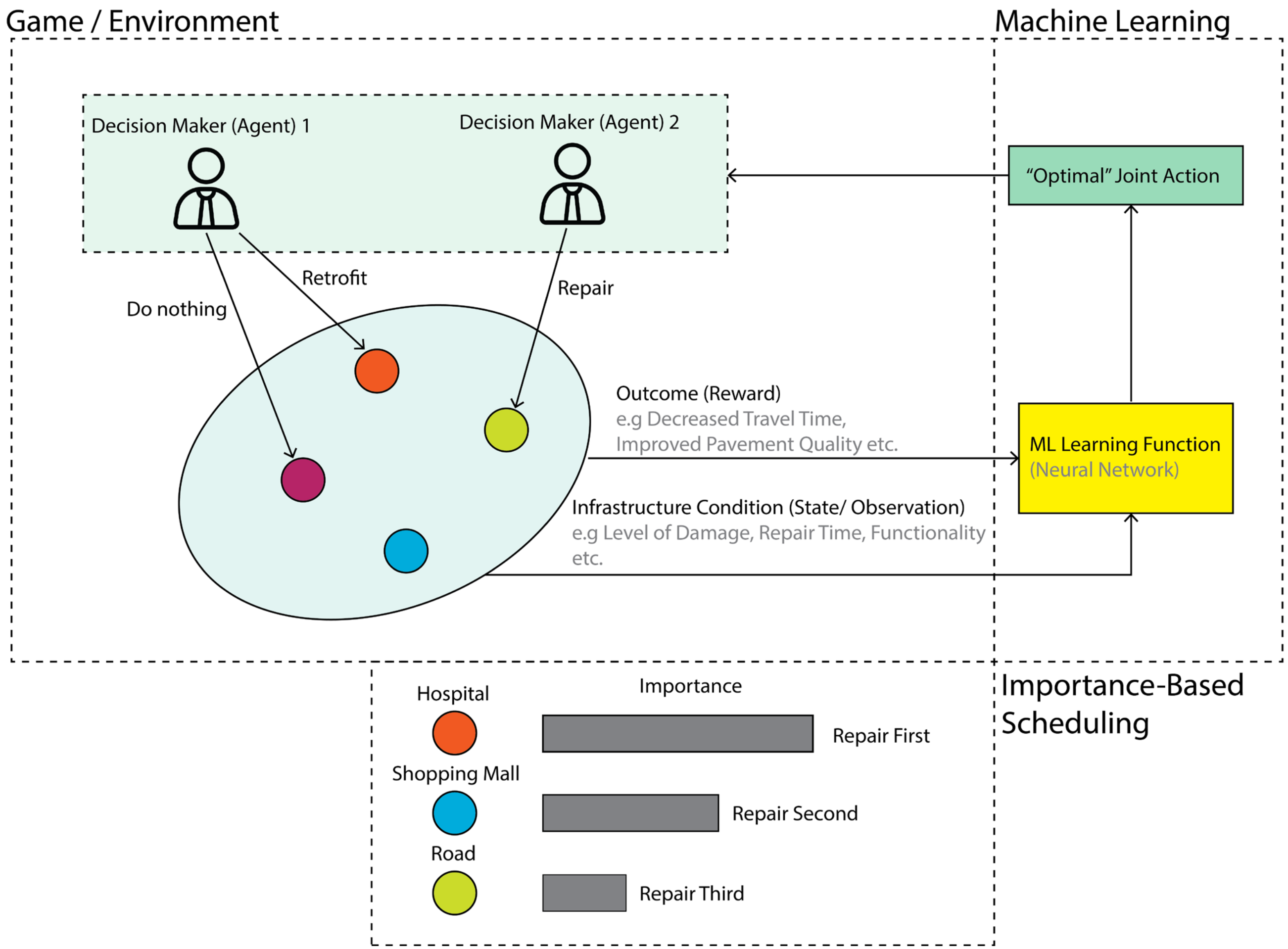
MARL can perform better than Importance-based repair scheduling of interdependent infrastructure networks.



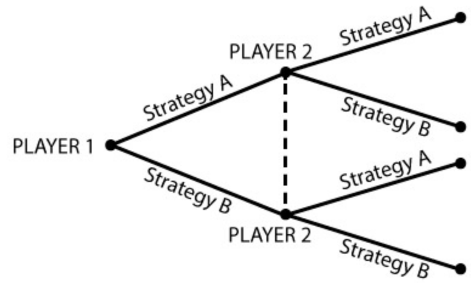
MARL vs Importance-Based decision making

Hypothesis

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



MARL vs Importance-Based decision making



Players, Decision Makers = Agents

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

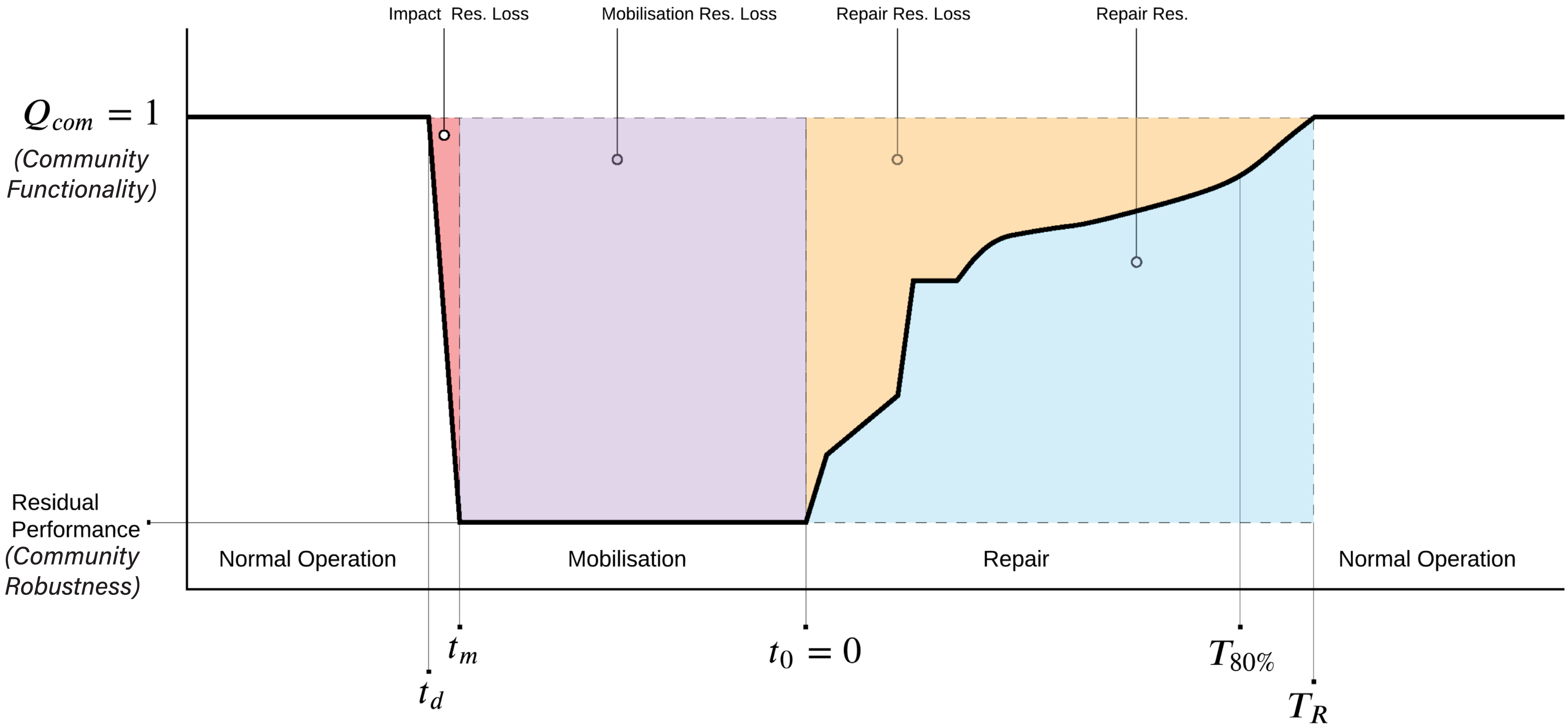
$$\text{Performance Index} = \frac{q(t)}{q^*(t)}$$

Examples Of General Importance-Based Ranking

How Do We Measure The Success Of A Repair Policy?

Measuring Success With Resilience

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



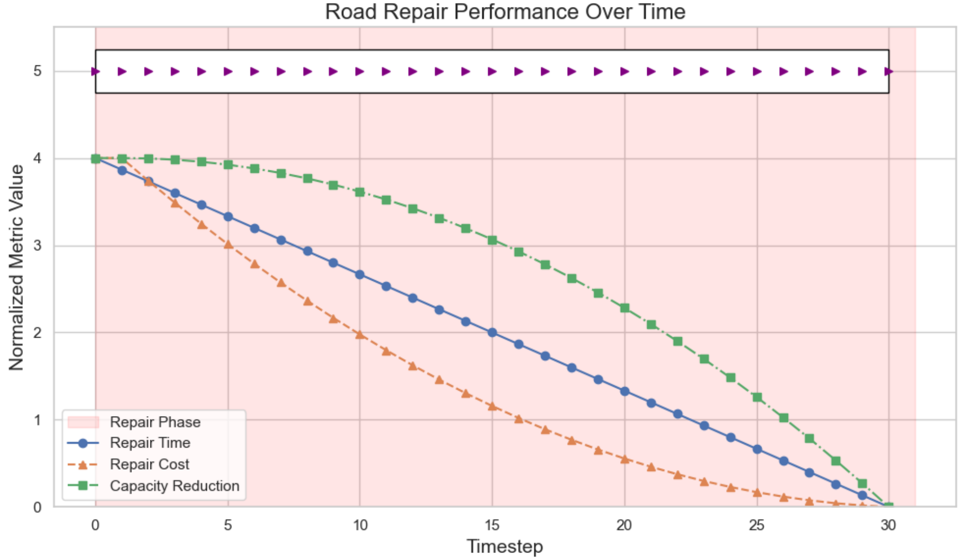
Community Functionality / Time

Measuring Functionality

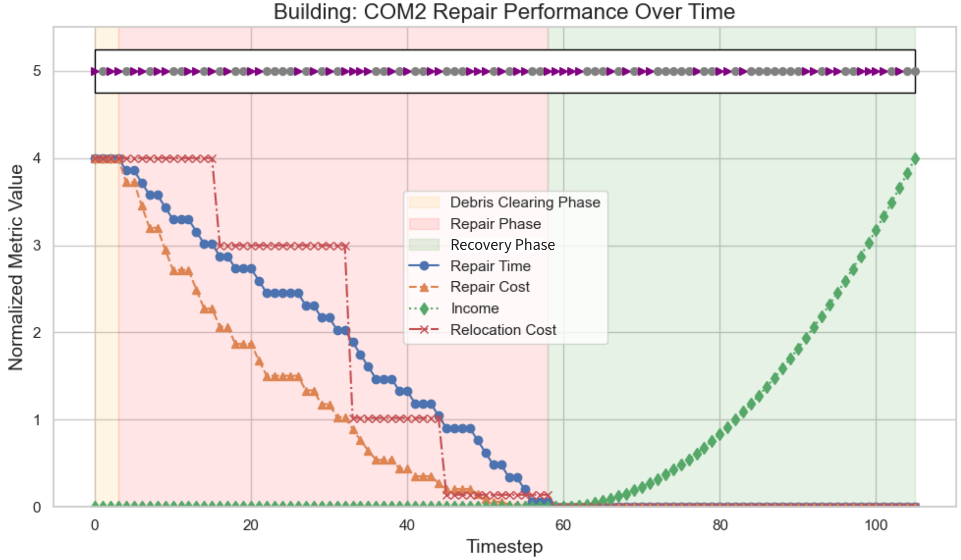
Community Functionality $$Q_{com} = \sum_{i}^{i=N_{sub}} w_i \cdot q_i(t)$$

Sub-system Functionality $$q_i(t) = 1 - L_i(t)$$

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



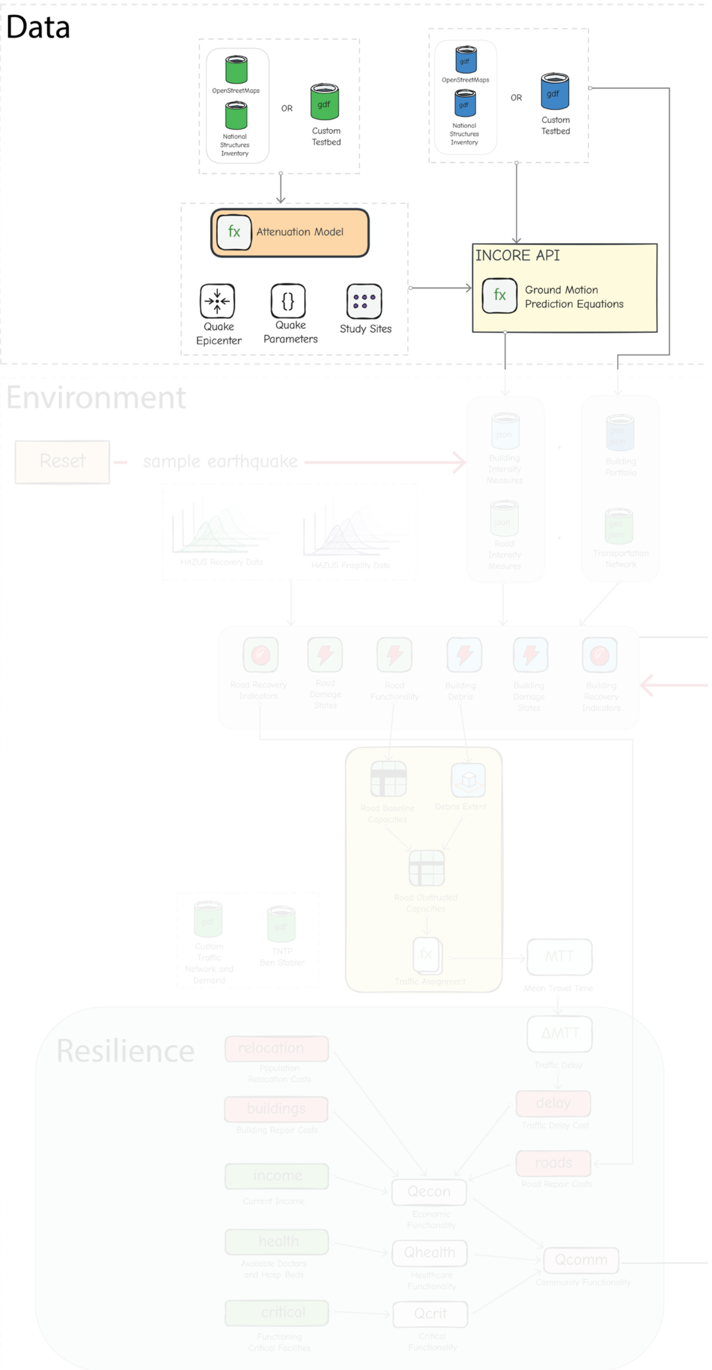
Optimal Repair (Repair at Every Timestep) of a Highway Road Segment

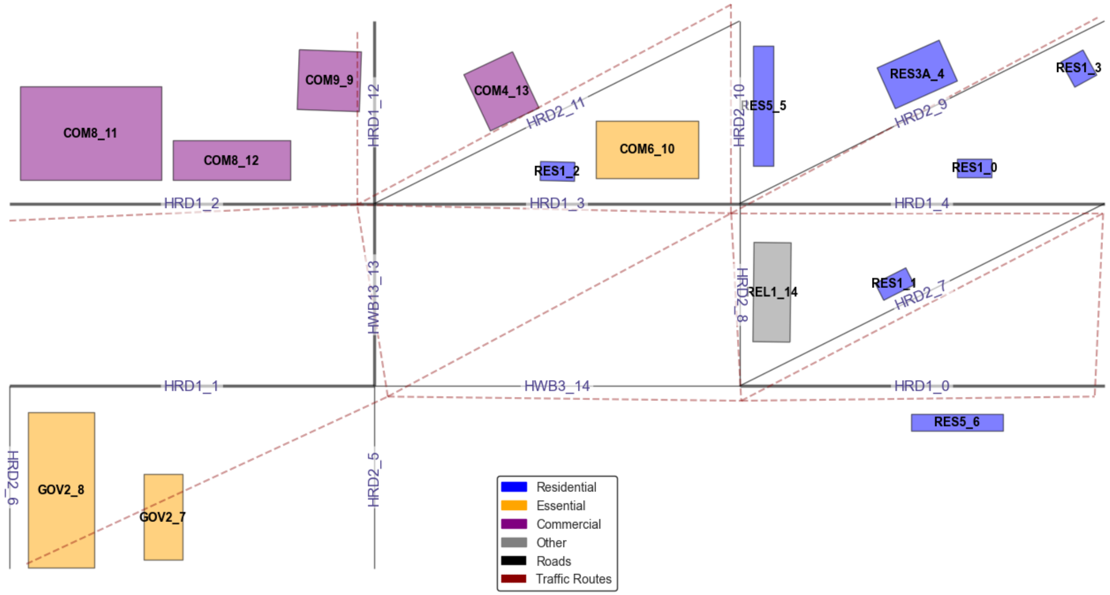


Sub-optimal Repair (Random Intervention at Every Timestep) of a large shopping mall

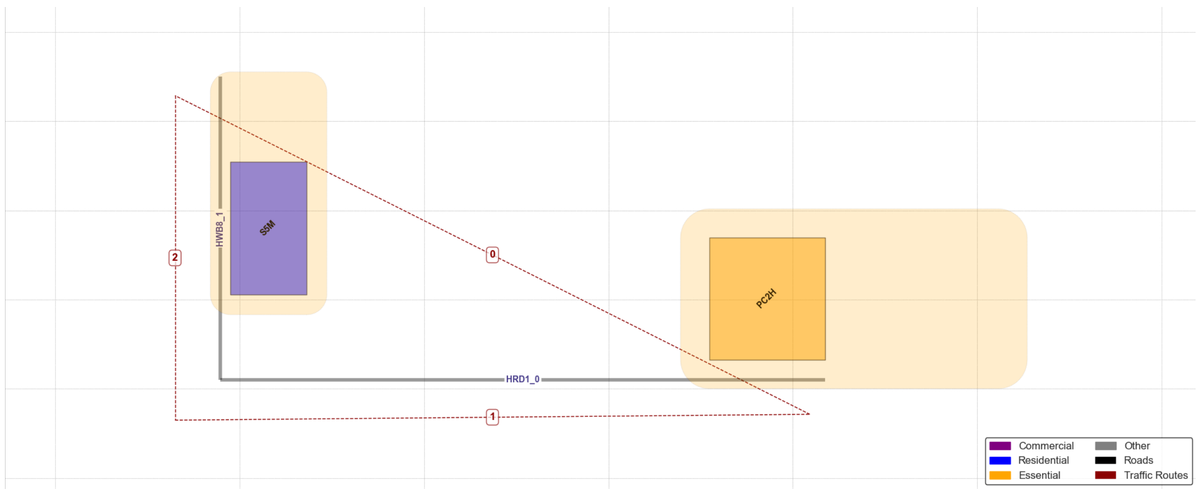
Methodology

Testbed Production

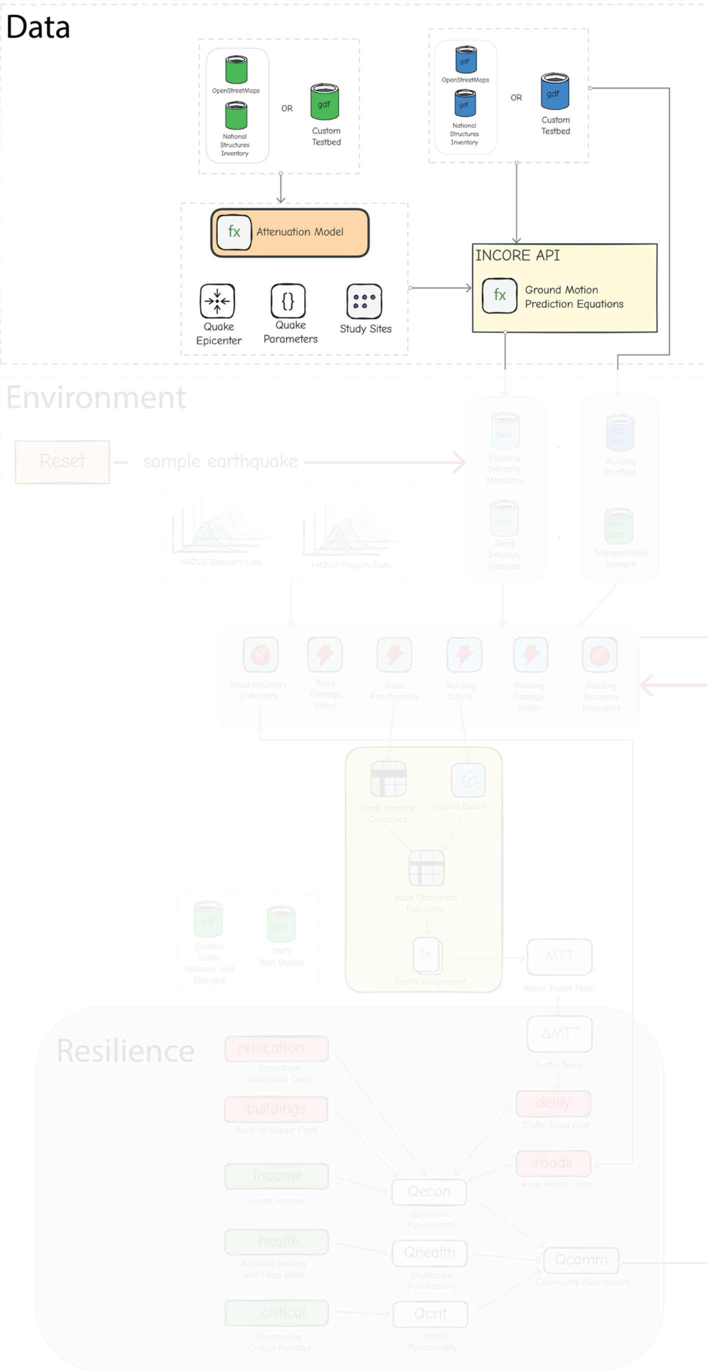




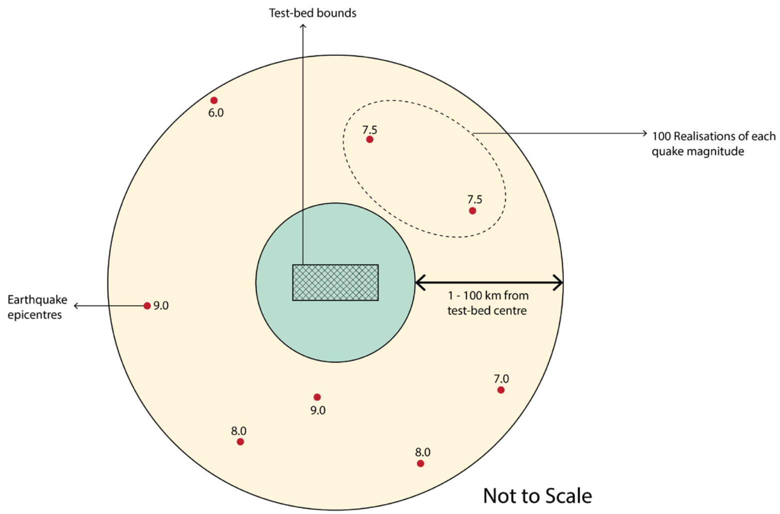
Toy City 30



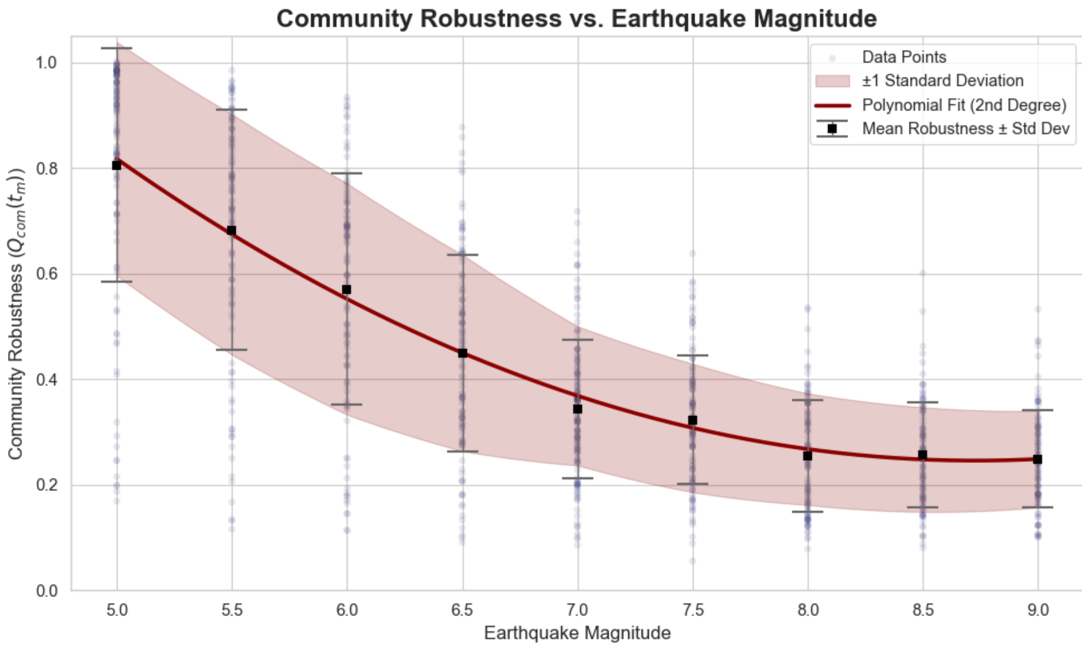
Toy City 4



Seismic Hazard Assessment

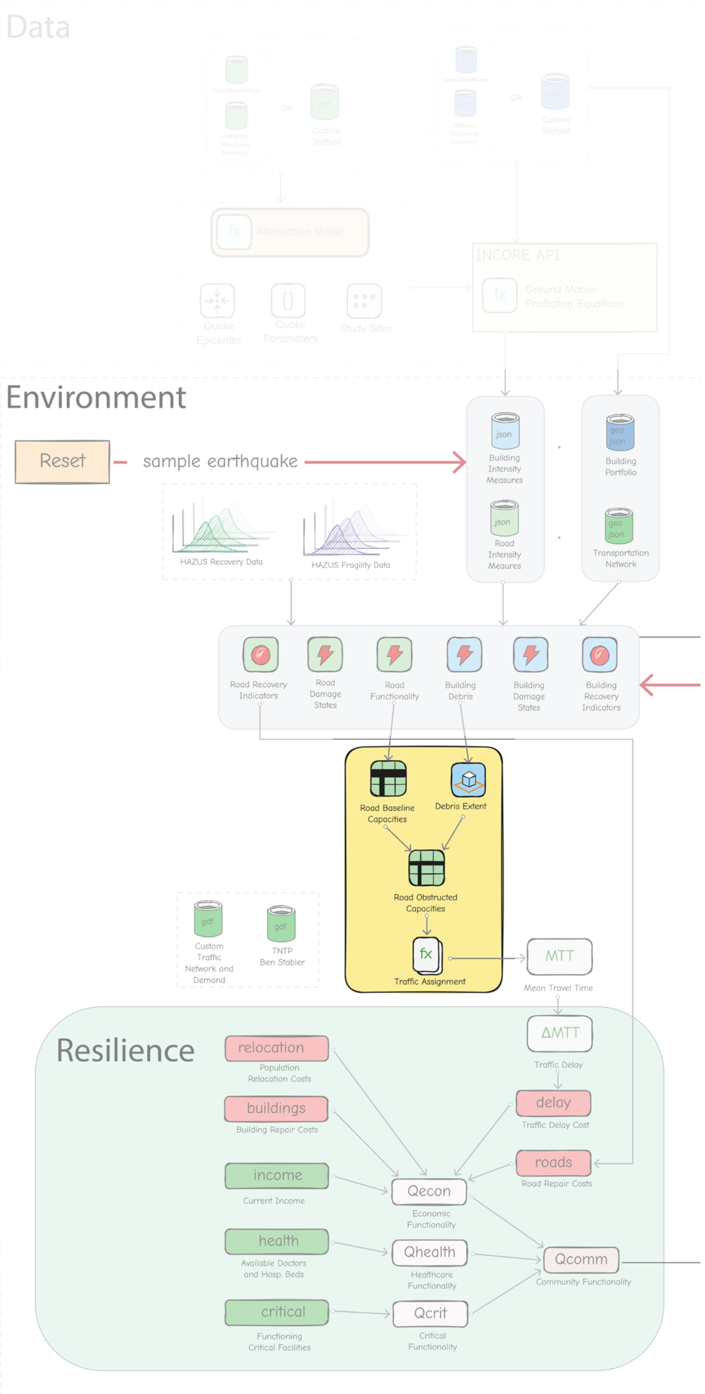


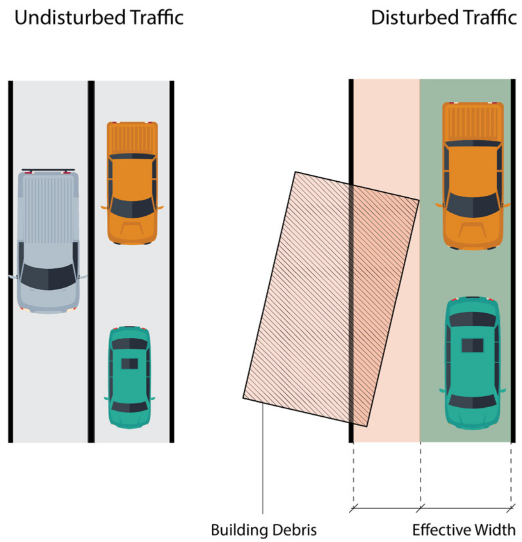
Dataset of Earthquakes from 5.0 - 9.0 M with 0.5 increments for 100 realisations per magnitude



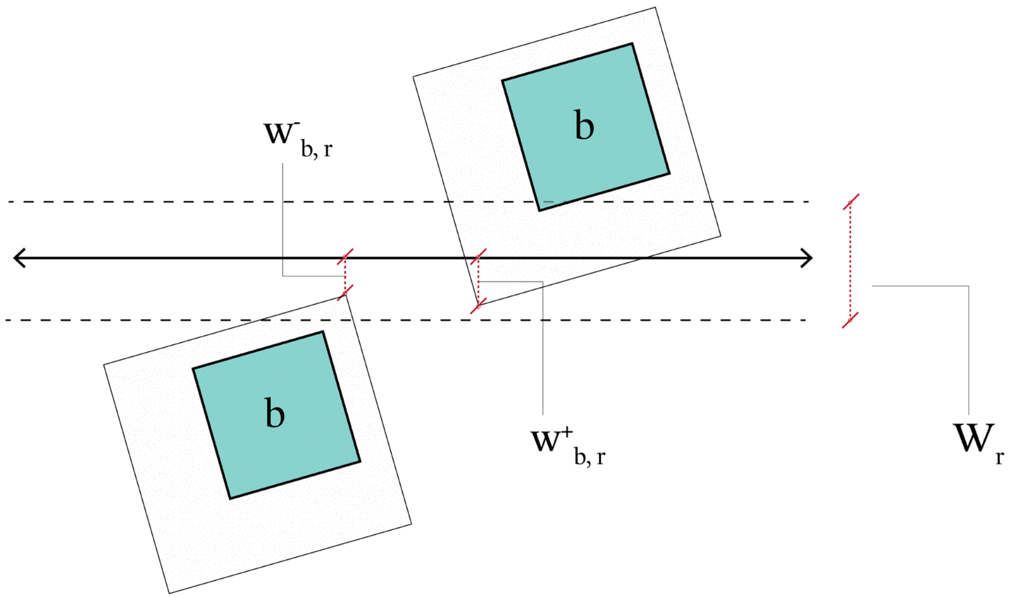
Results of Earthquake Impact to Community Functionality

Traffic



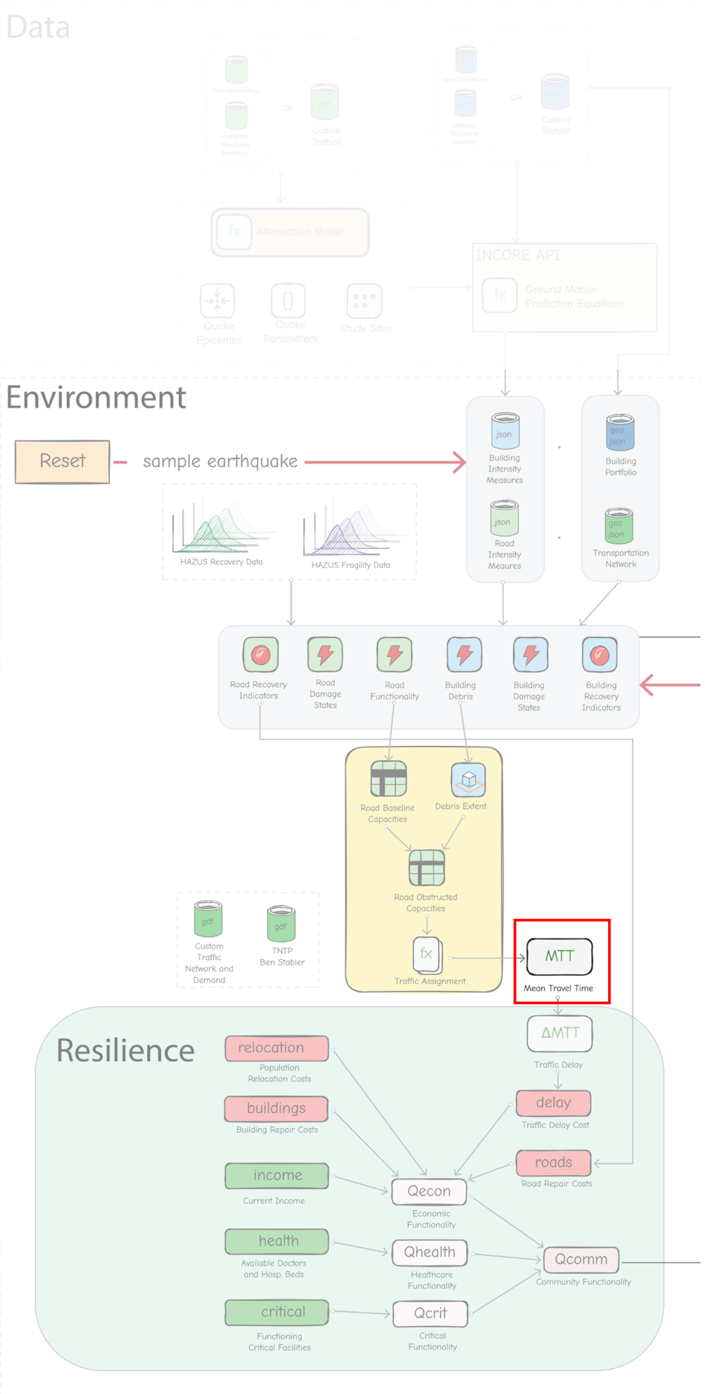


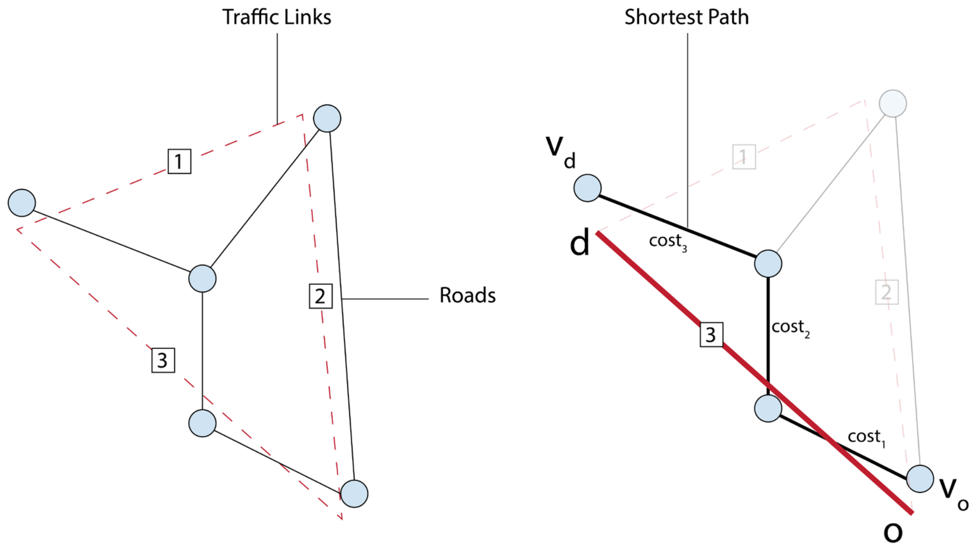
Effect of Debris on Traffic Link Capacity



Traffic Link Capacity Calculation

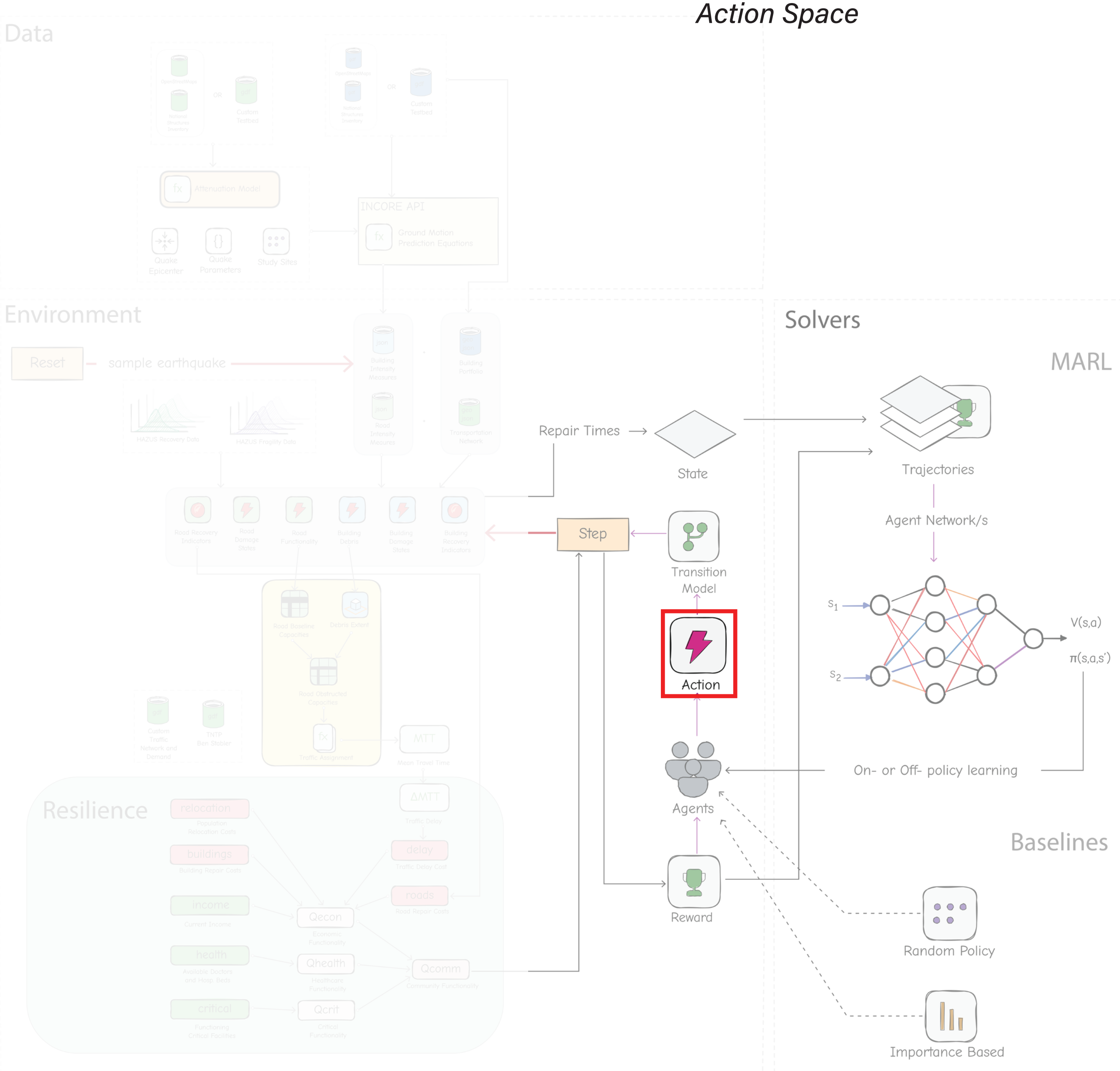
Traffic





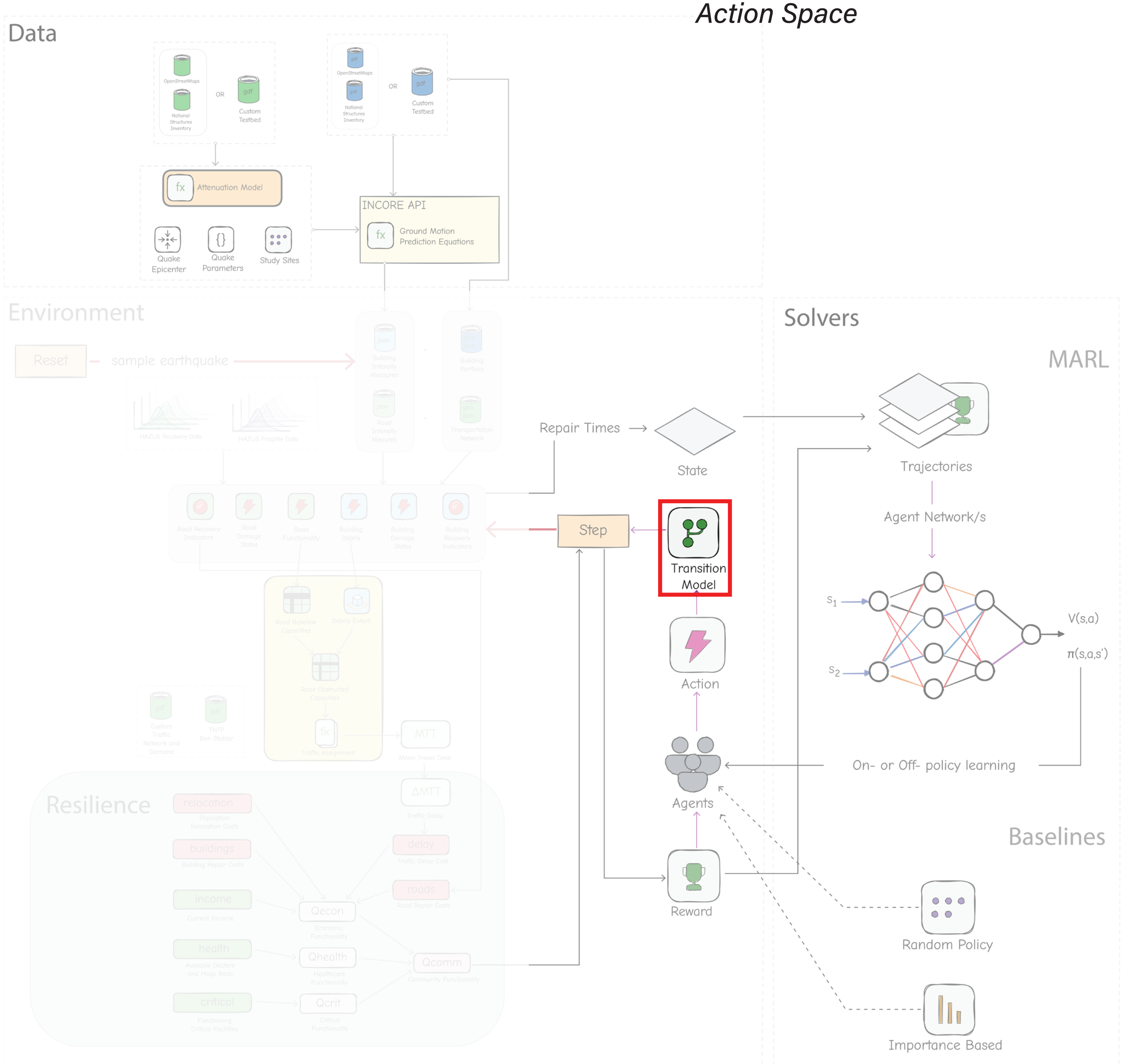
Traffic Link to Road Mapping

Action Space



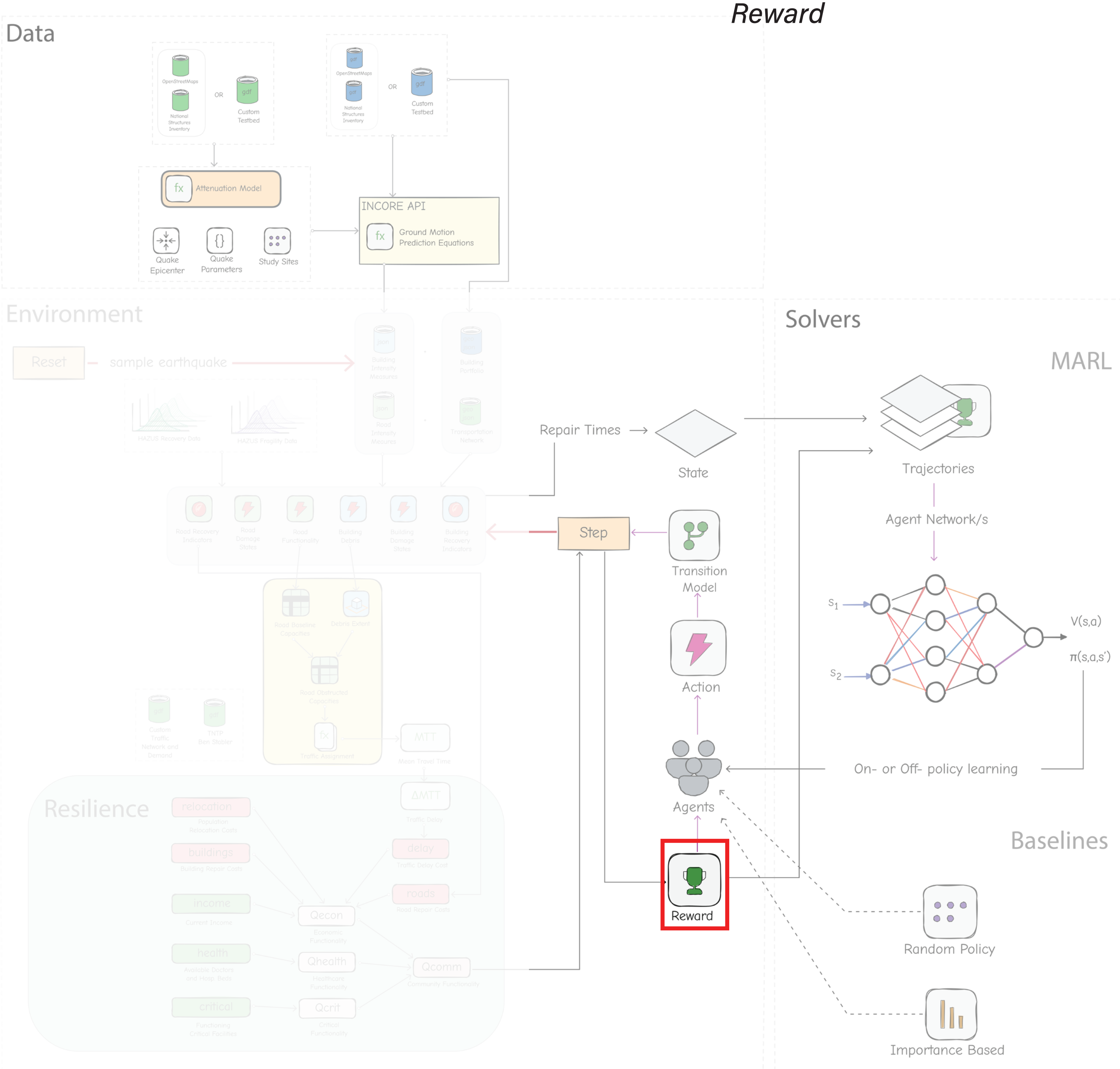
Action 0 - Do Nothing
Action 1 - Repair

Action Space



Road Repair Constraint
Repair Crew Constraint

Reward



Data
OR
Custom Testbed
Attenuation Model
Quake Epicenter
Quake Parameters
Study Sites
INCORE API
Ground Motion Prediction Equations
Environment
Reset
sample earthquake
Repair Times
State
Step
Transition Model
Action
Agents
Reward
Resilience
Solvers
MARL
Trajectories
Agent Network/s
V(s,a)
π(s,a,s')
On- or Off- policy learning
Baselines
Random Policy
Importance Based

Reward

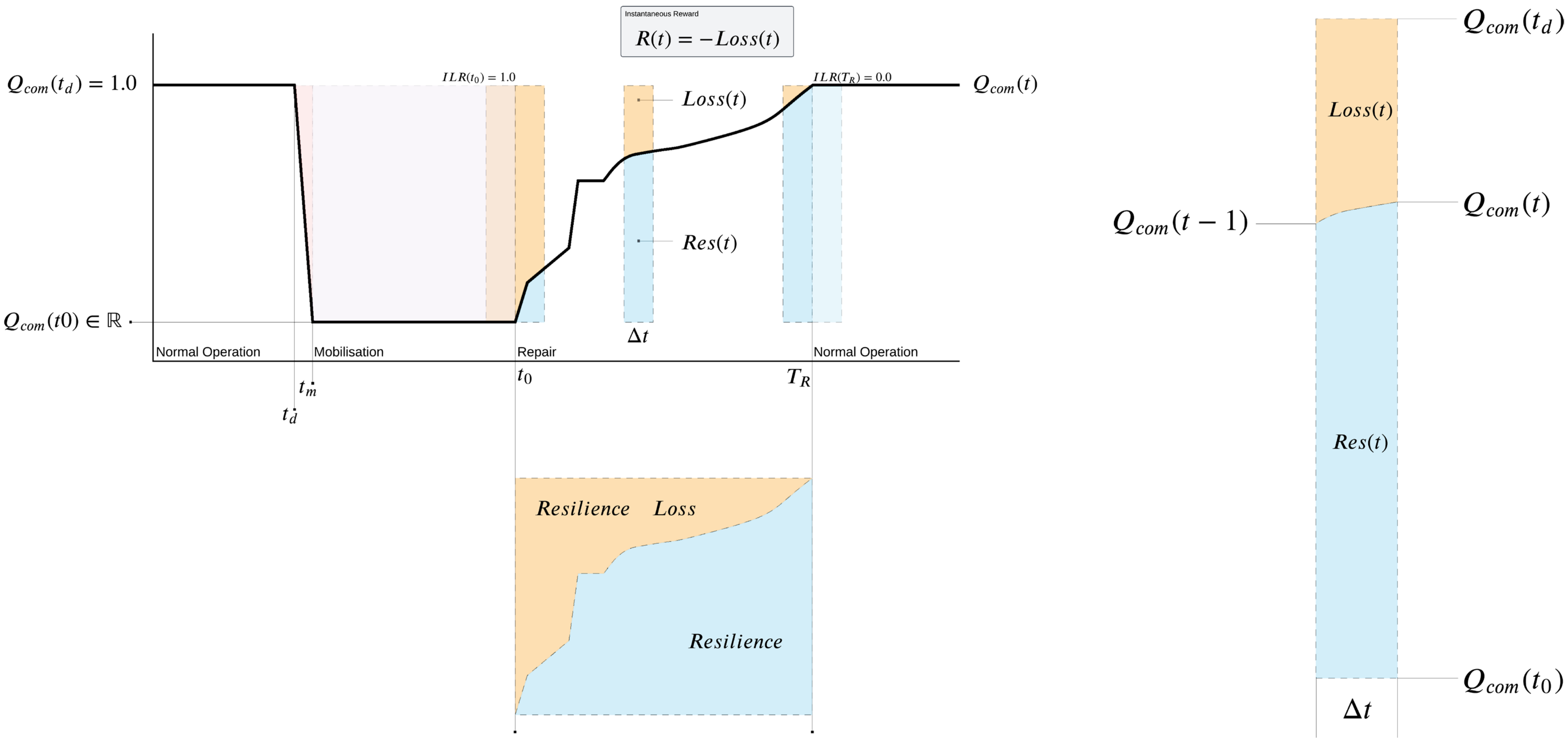
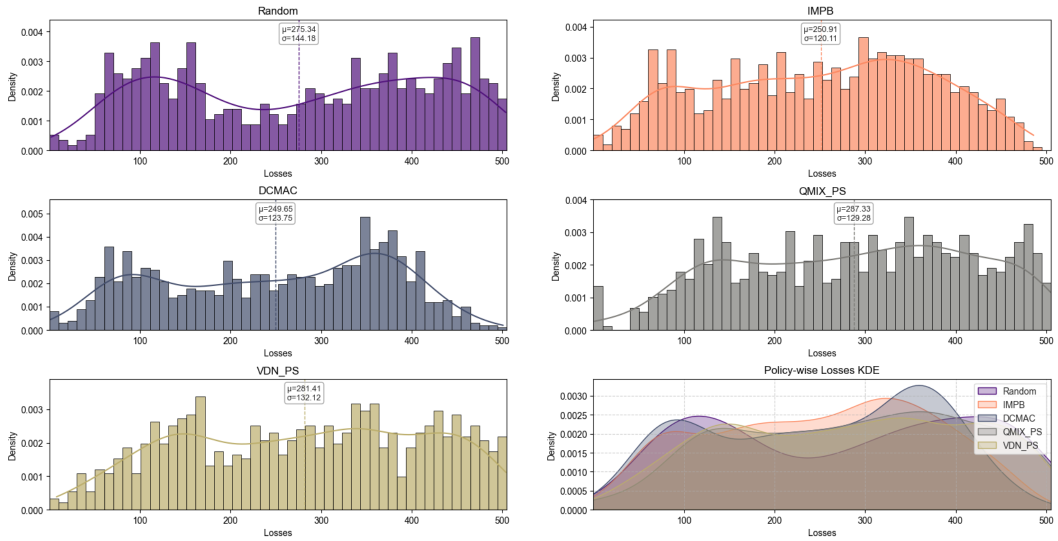


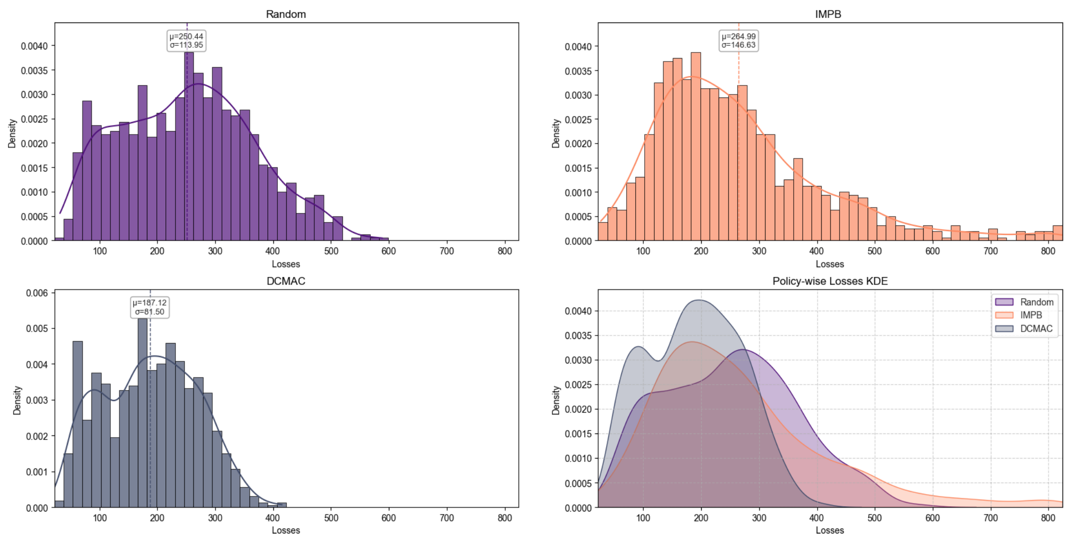
Illustration of Reward Function

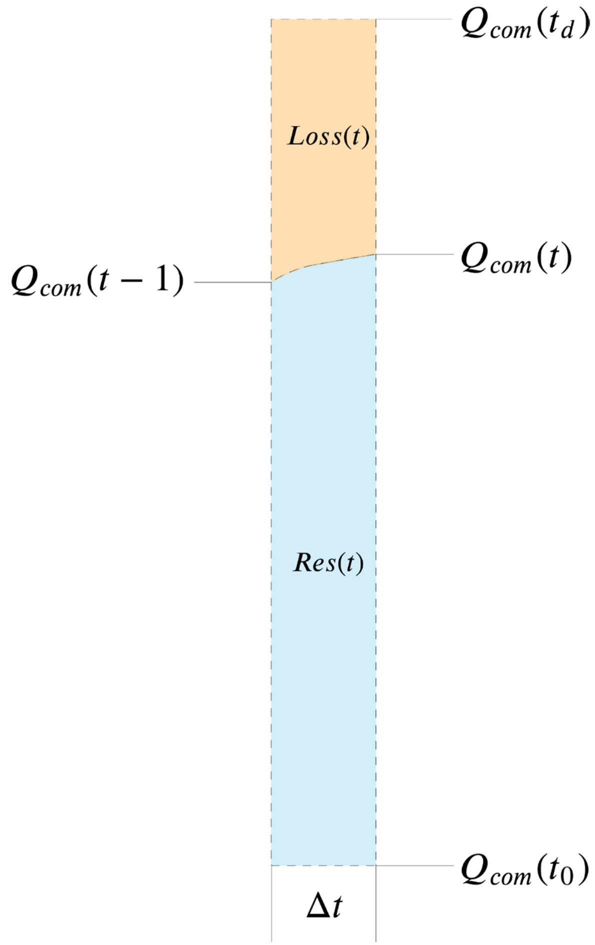
Results

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

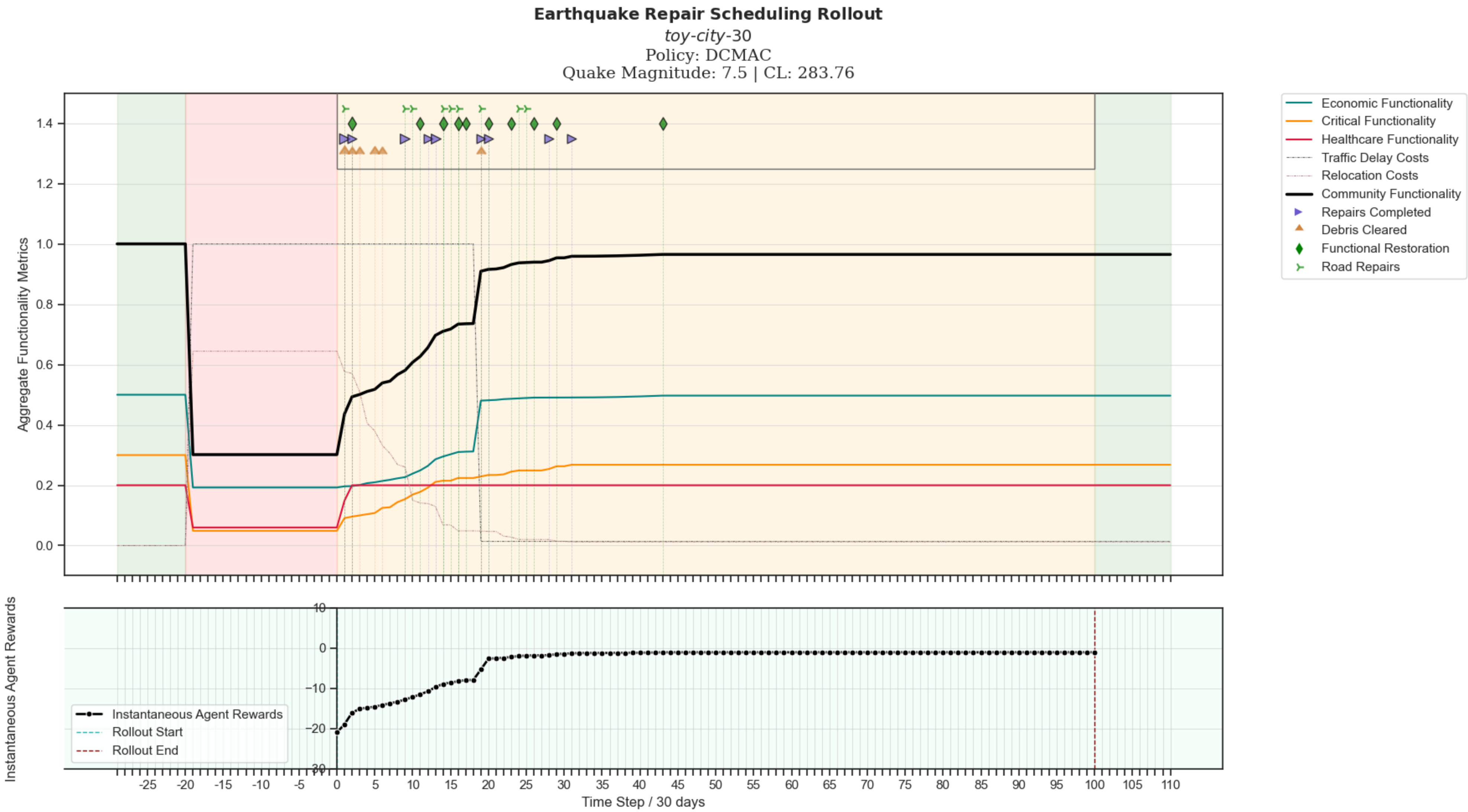


70% Recovery Cumulative Losses (CL – 70) Distributions per Policy, over 1000 Rollouts, toy-city-30





Deep Centralised Multi Agent Actor Critic (DCMAC)

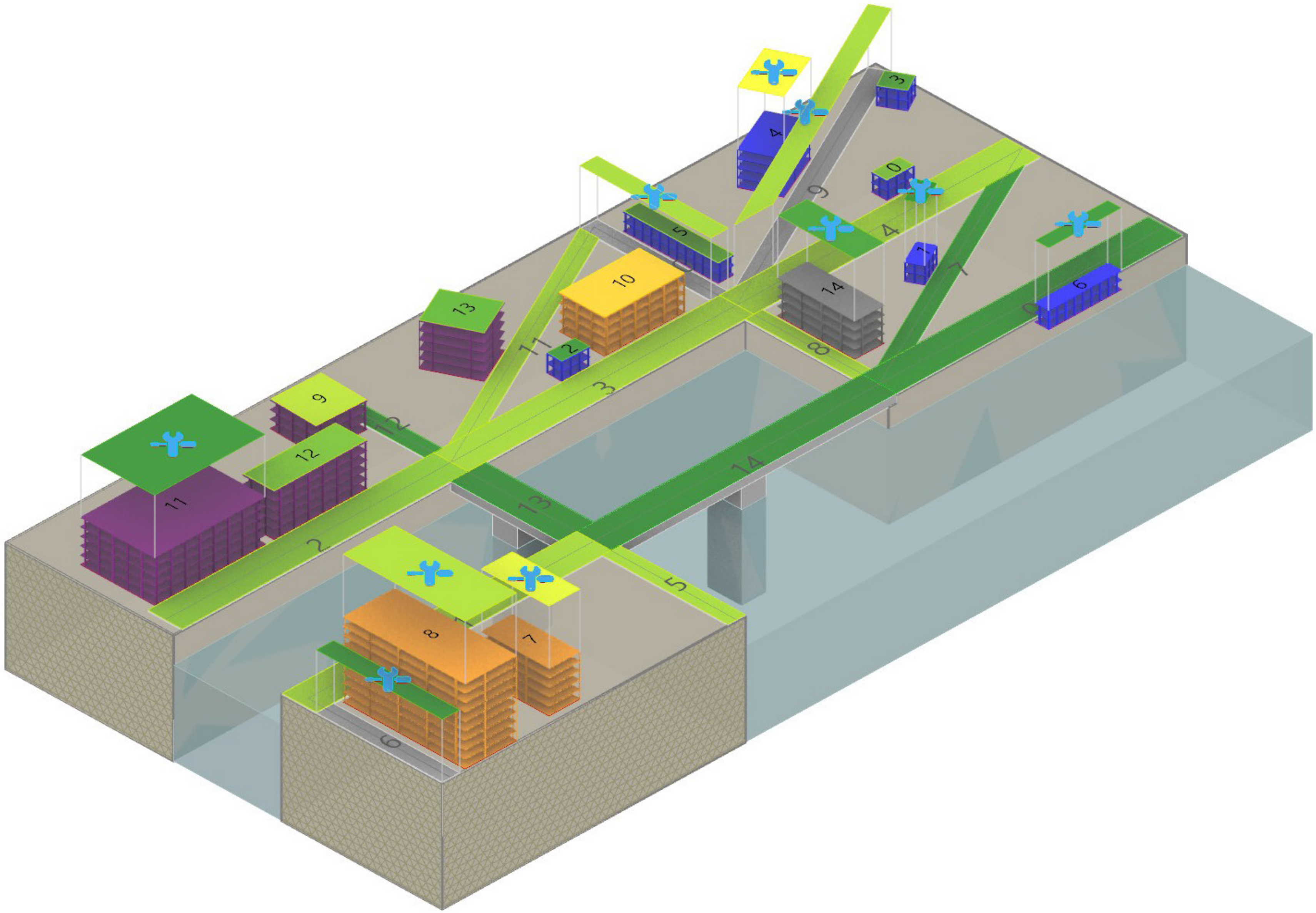


DCMAC

Repair time = 0 days

Repair time = 500 days

t = 1

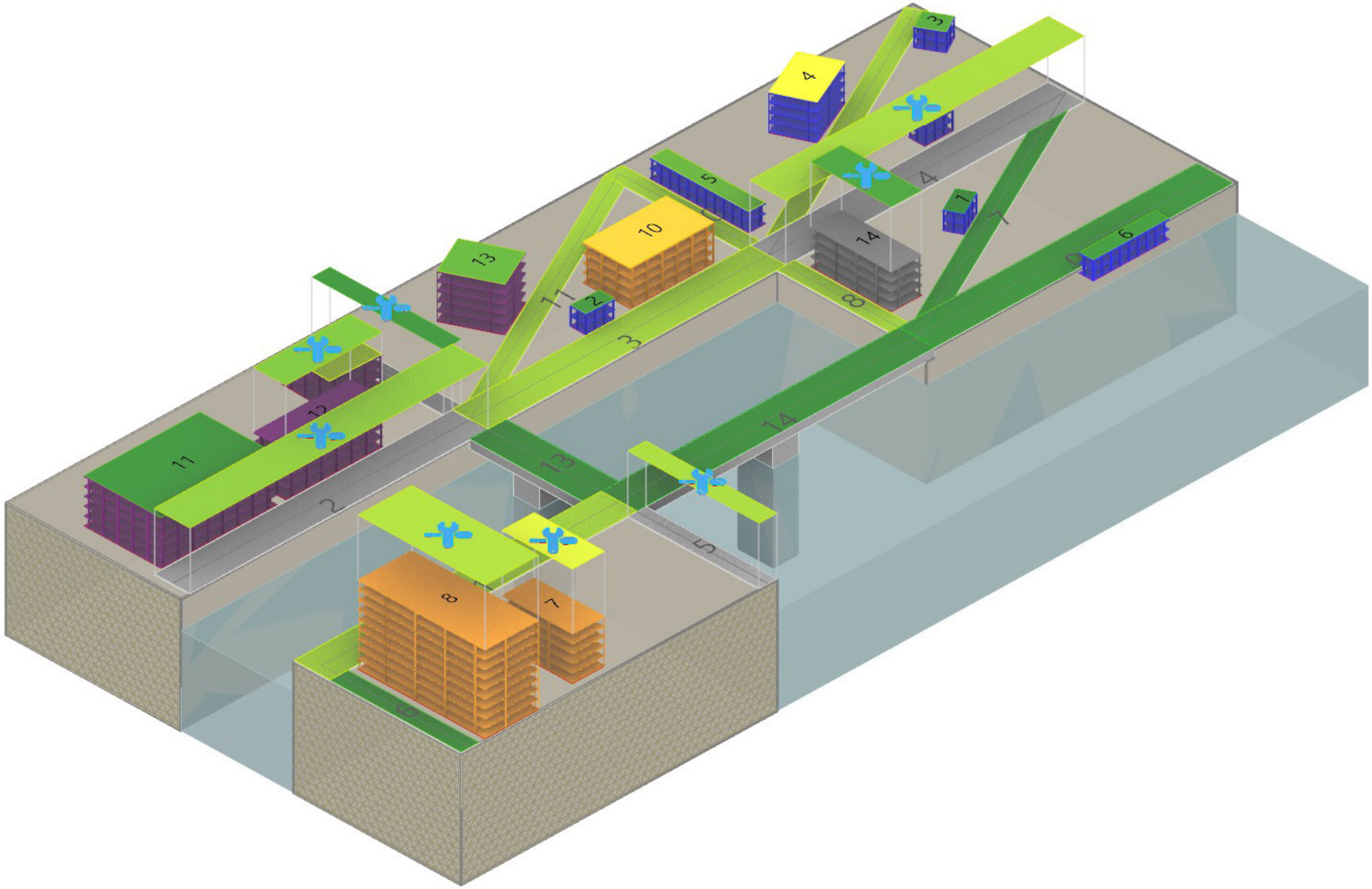


DCMAC

Repair time = 0 days

Repair time = 500 days

t = 2



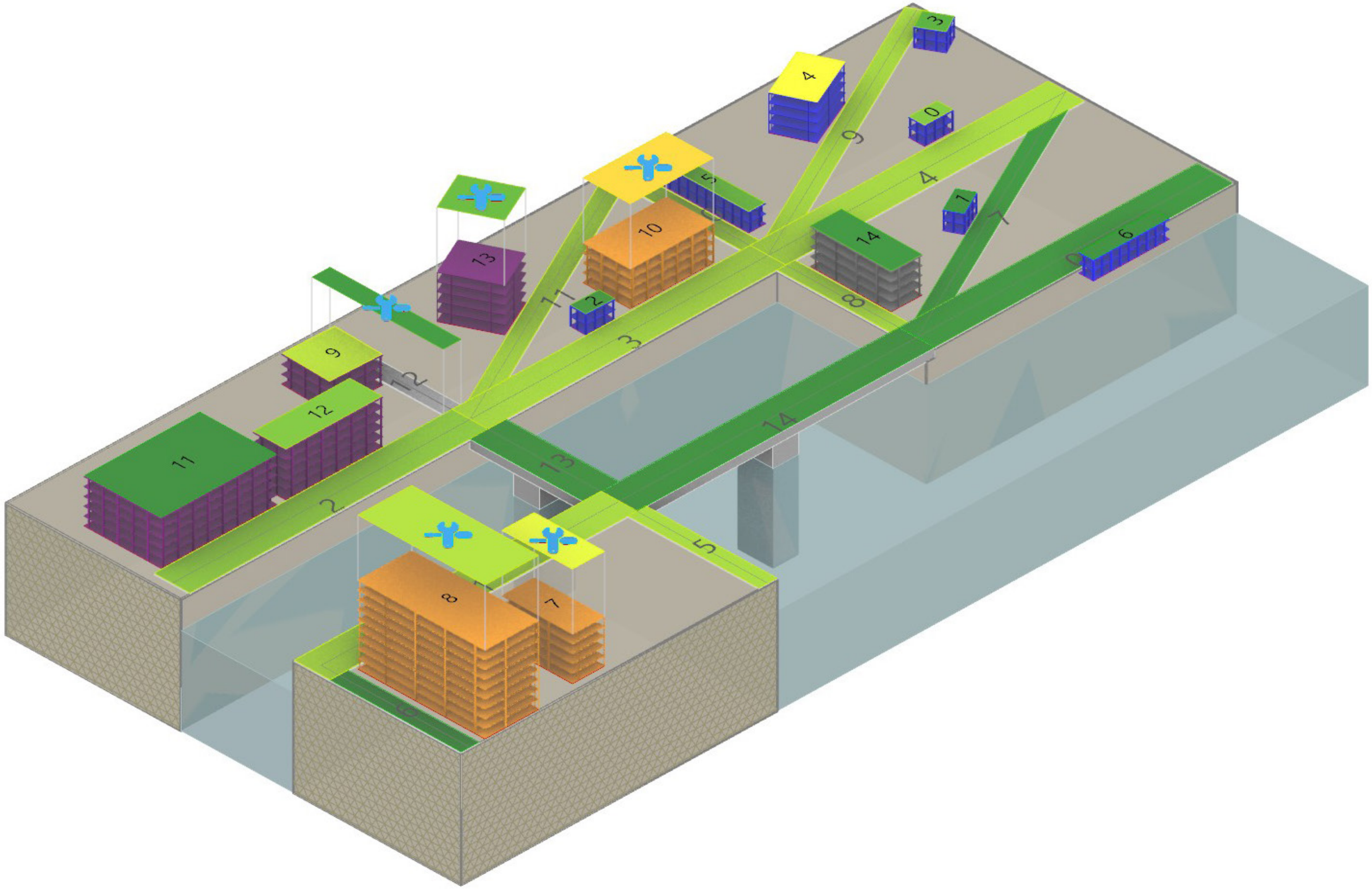
Context · Fragility · Recovery · Resilience · Traffic · Reinforcement Learning · Reward · *Experiment* · Conclusion

DCMAC

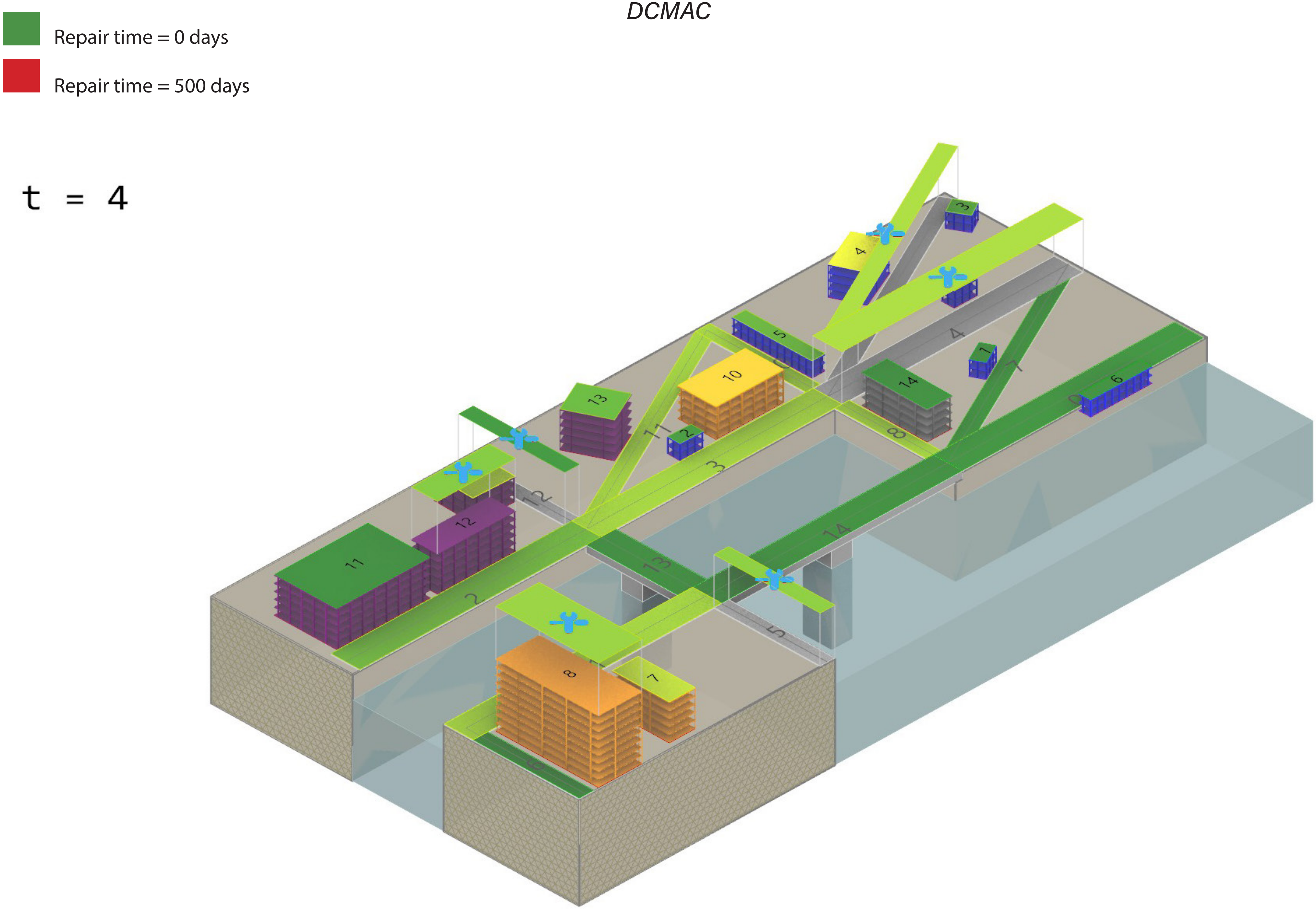
Repair time = 0 days

Repair time = 500 days

t = 3



DCMAC

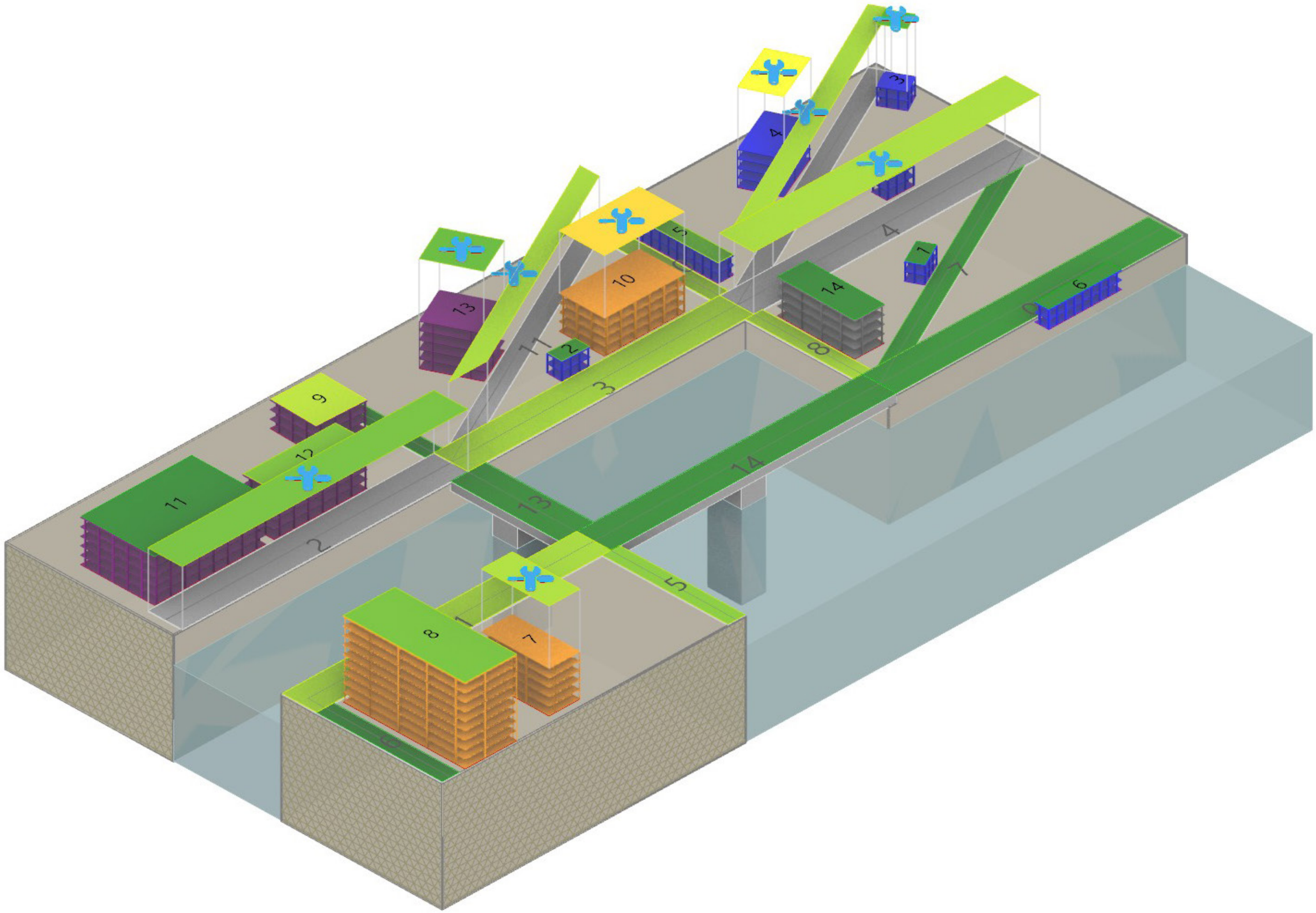


DCMAC

Repair time = 0 days

Repair time = 500 days

t = 5

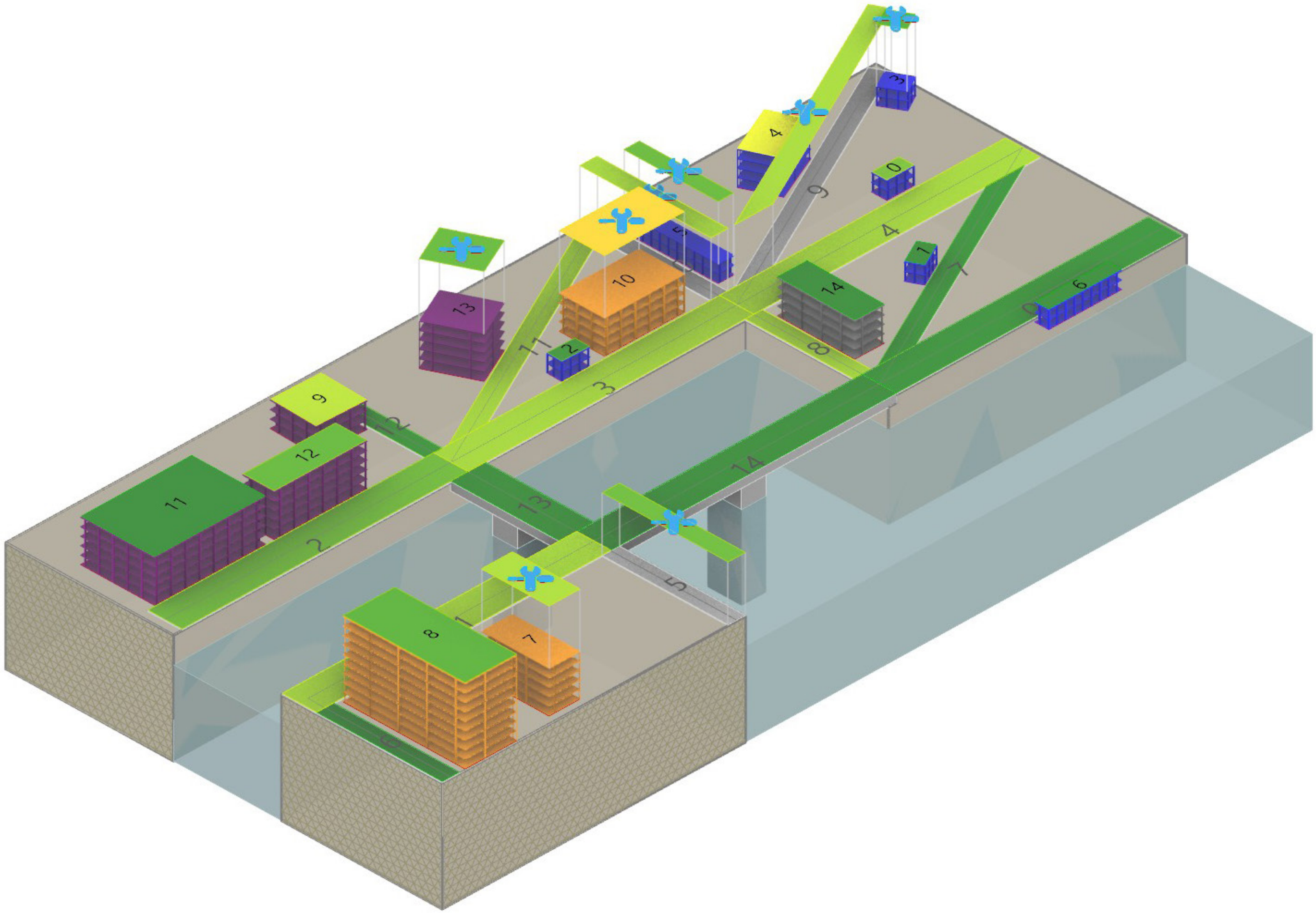


DCMAC

Repair time = 0 days

Repair time = 500 days

t = 6

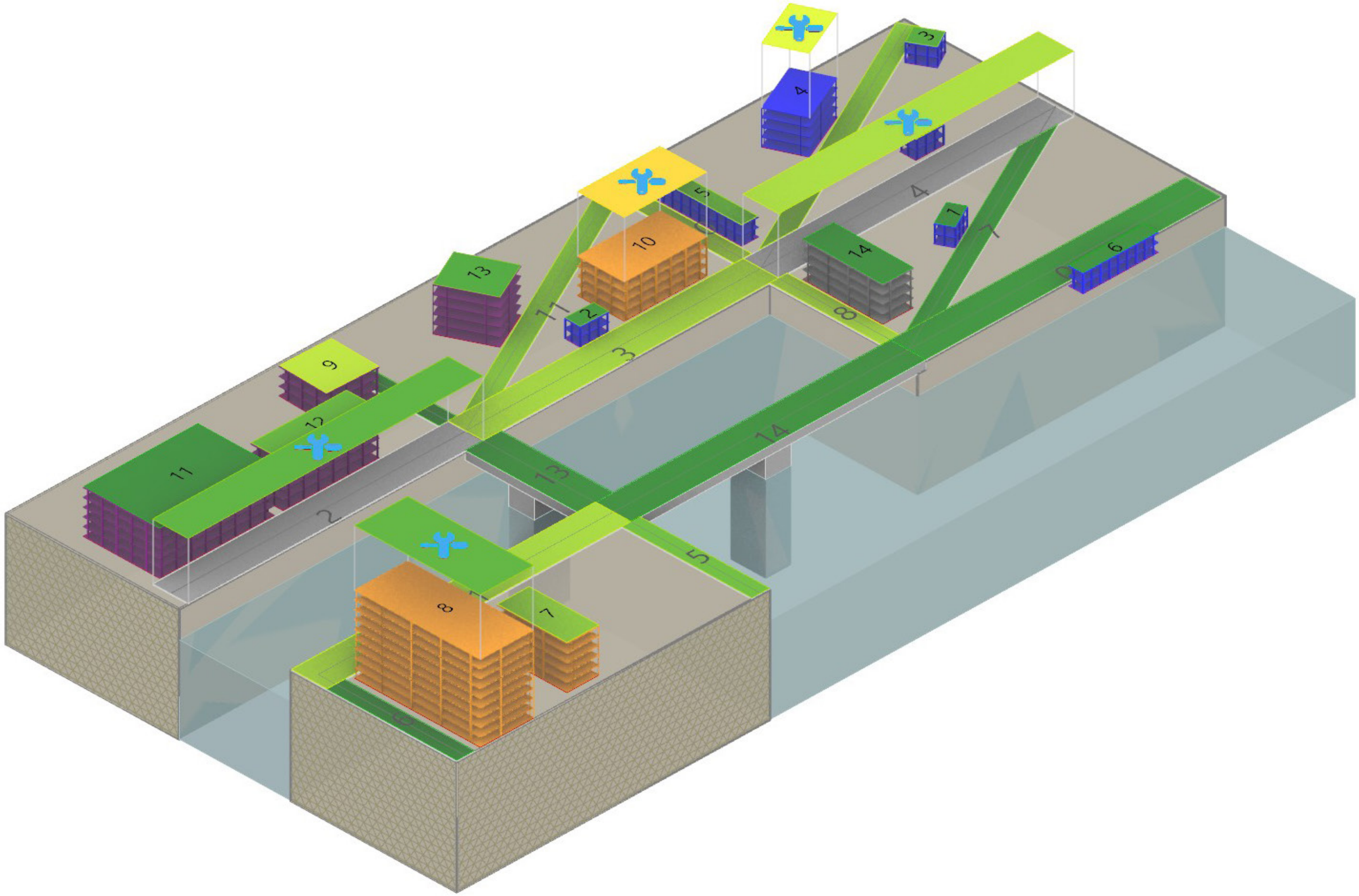


DCMAC

Repair time = 0 days

Repair time = 500 days

t = 7

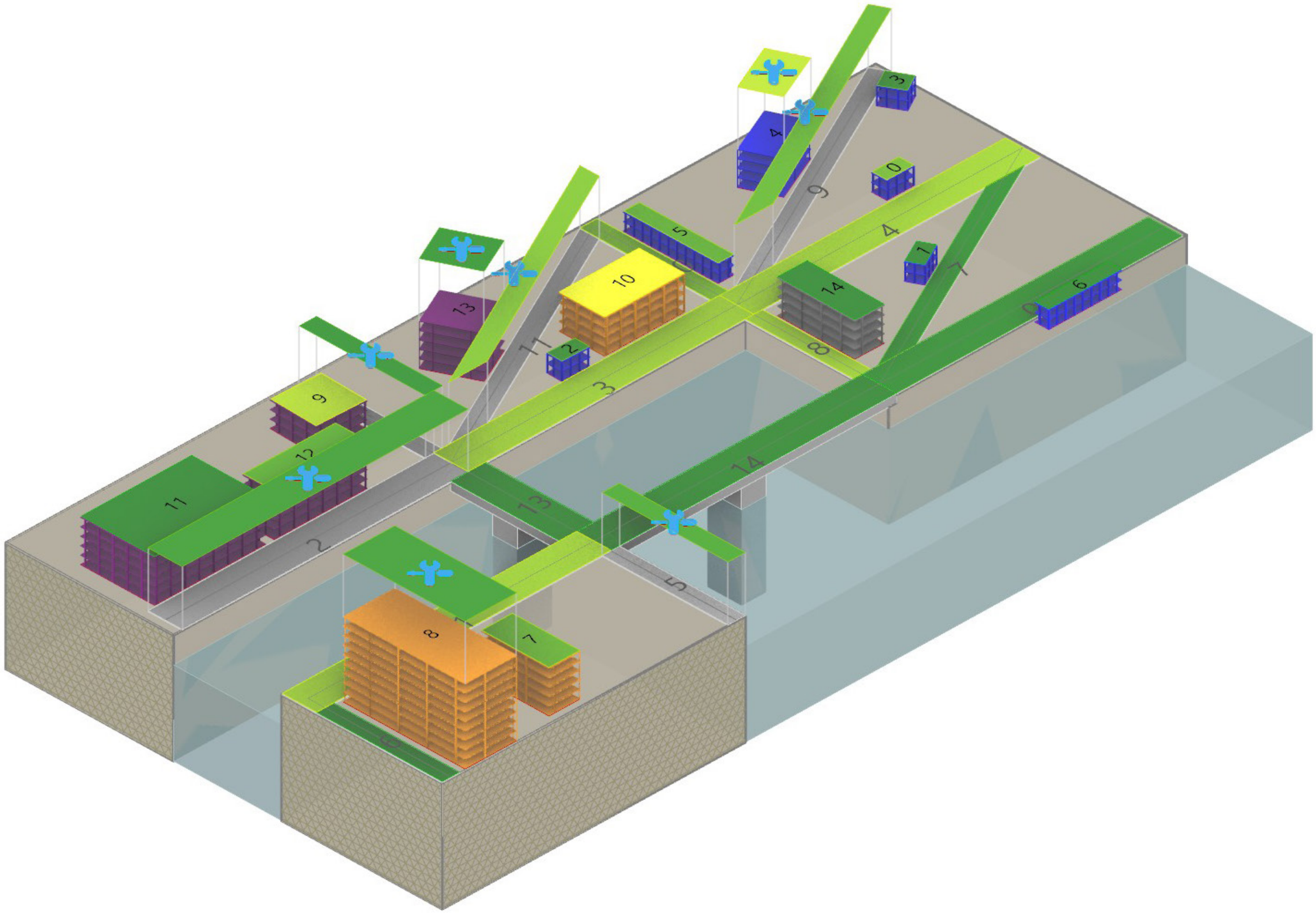


DCMAC

Repair time = 0 days

Repair time = 500 days

t = 9

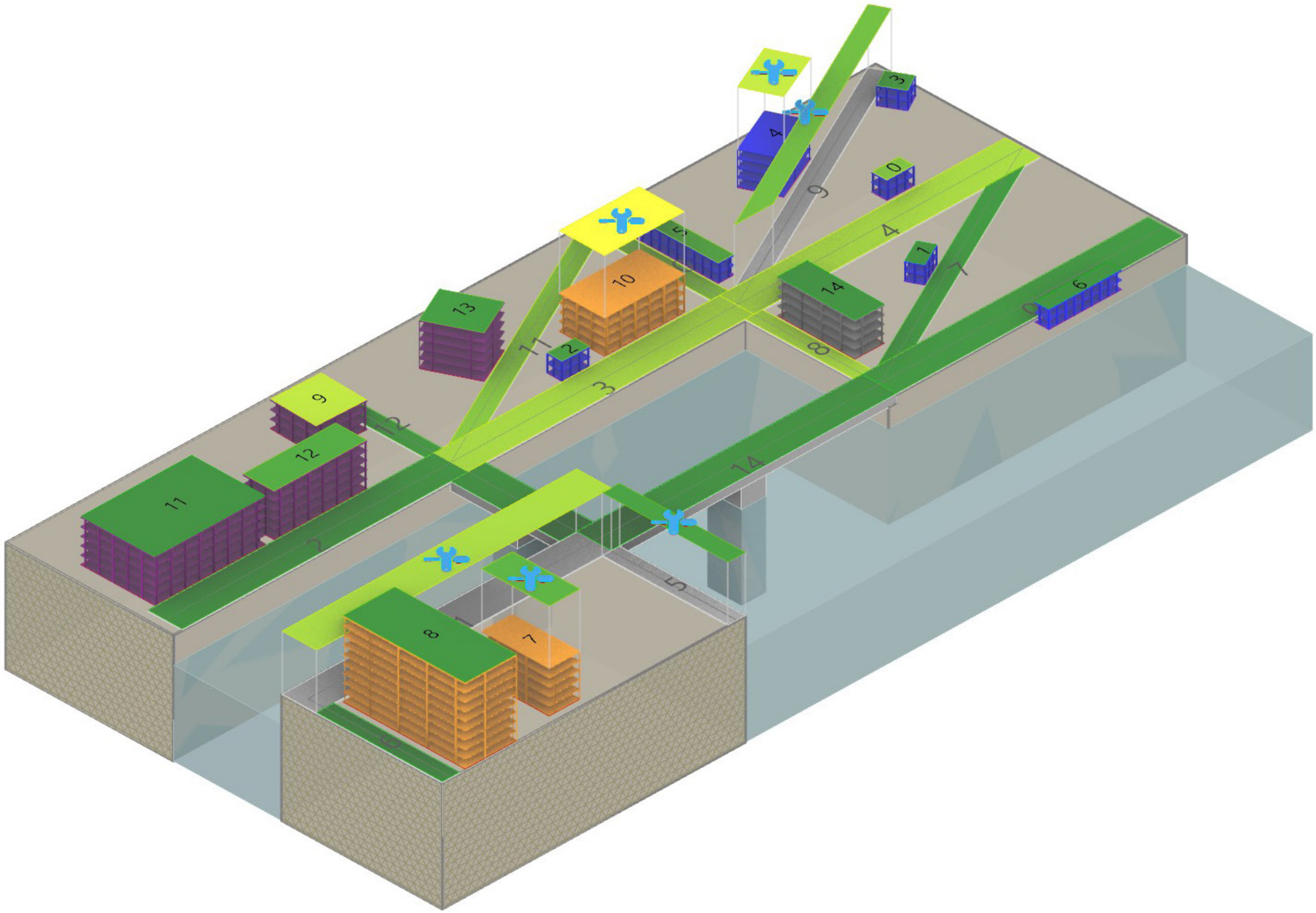


DCMAC

Repair time = 0 days

Repair time = 500 days

t = 10



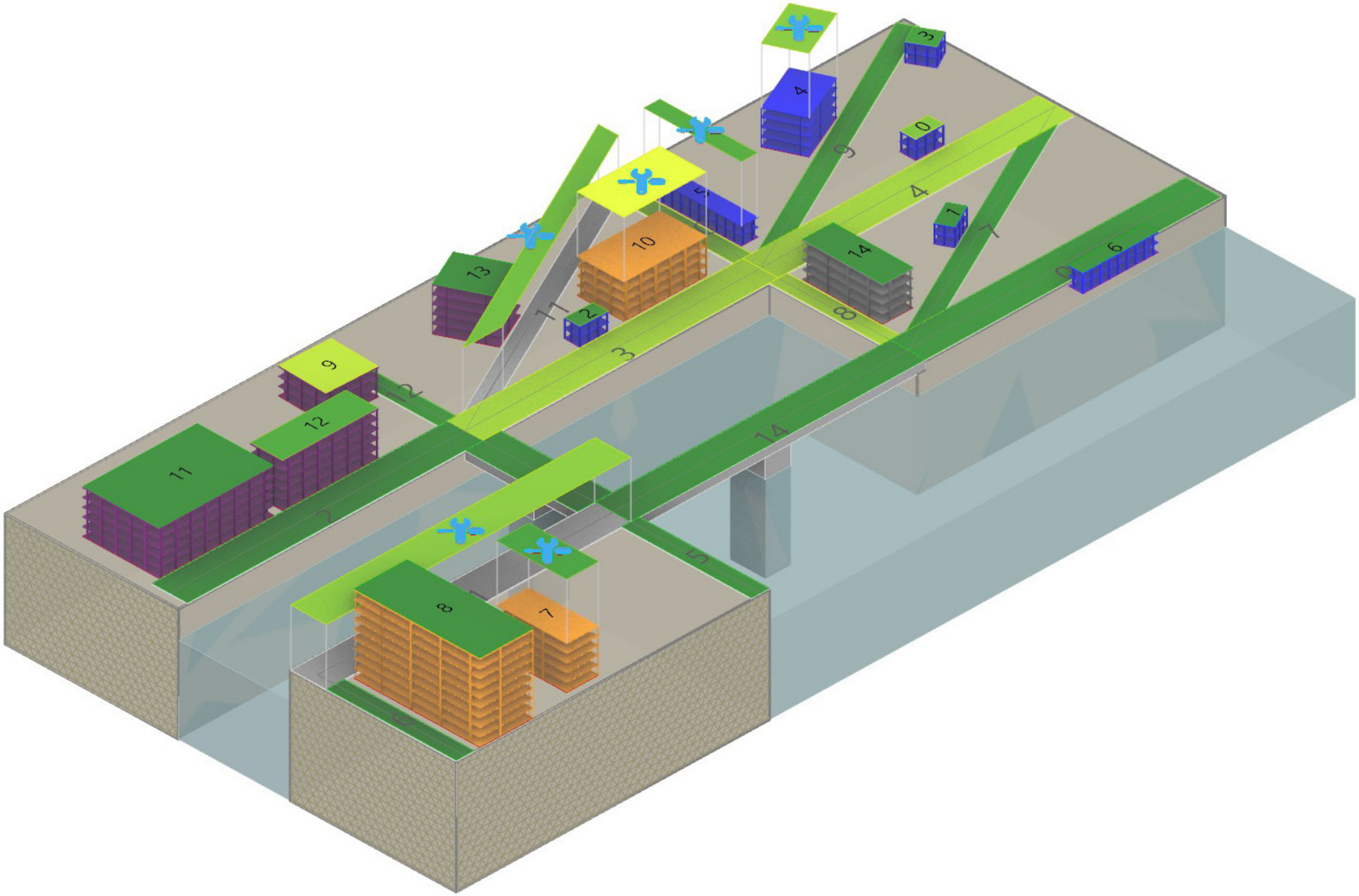
Context · Fragility · Recovery · Resilience · Traffic · Reinforcement Learning · Reward · ***Experiment*** · Conclusion

DCMAC

Repair time = 0 days

Repair time = 500 days

t = 12

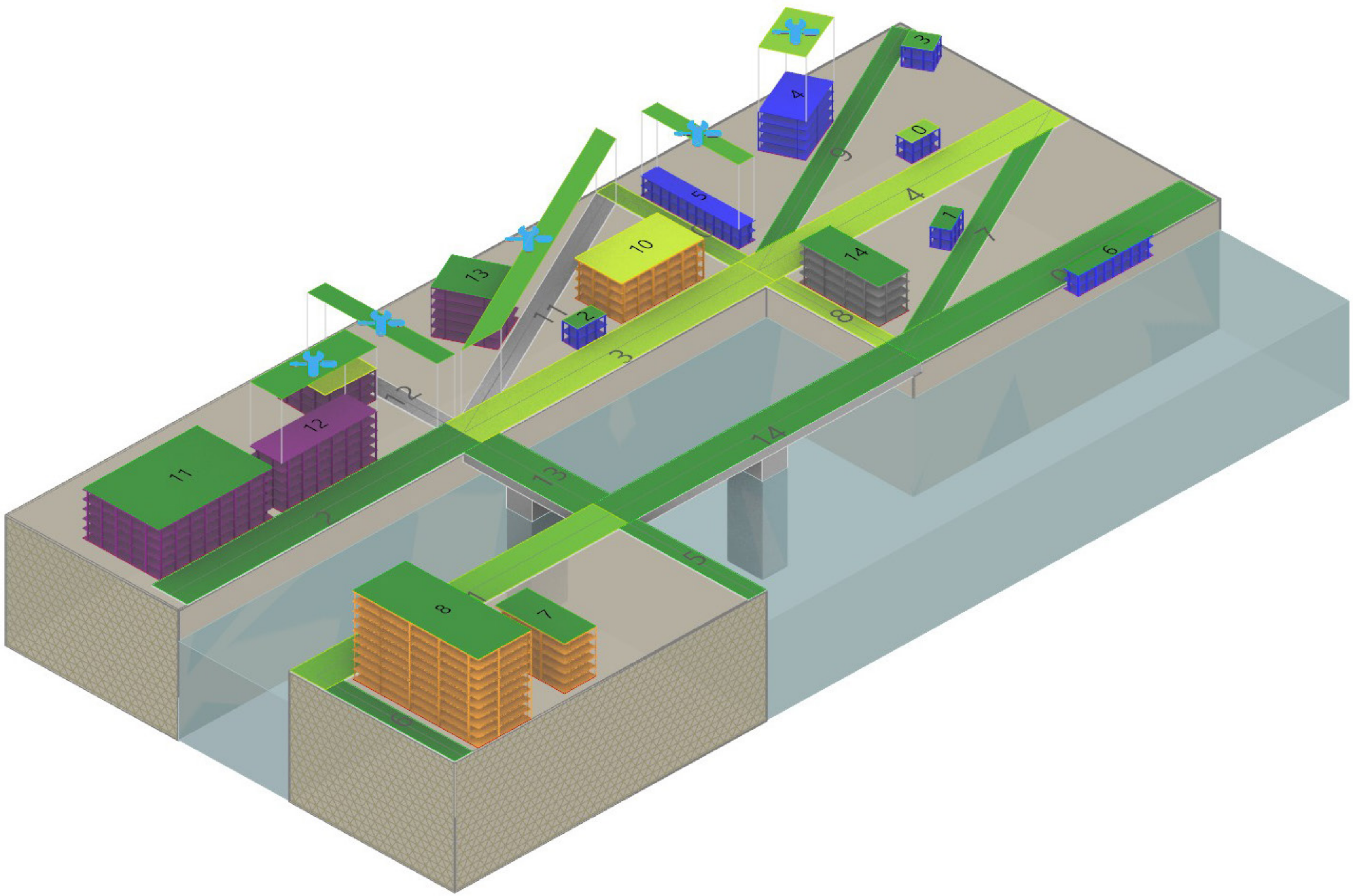


DCMAC

Repair time = 0 days

Repair time = 500 days

t = 13



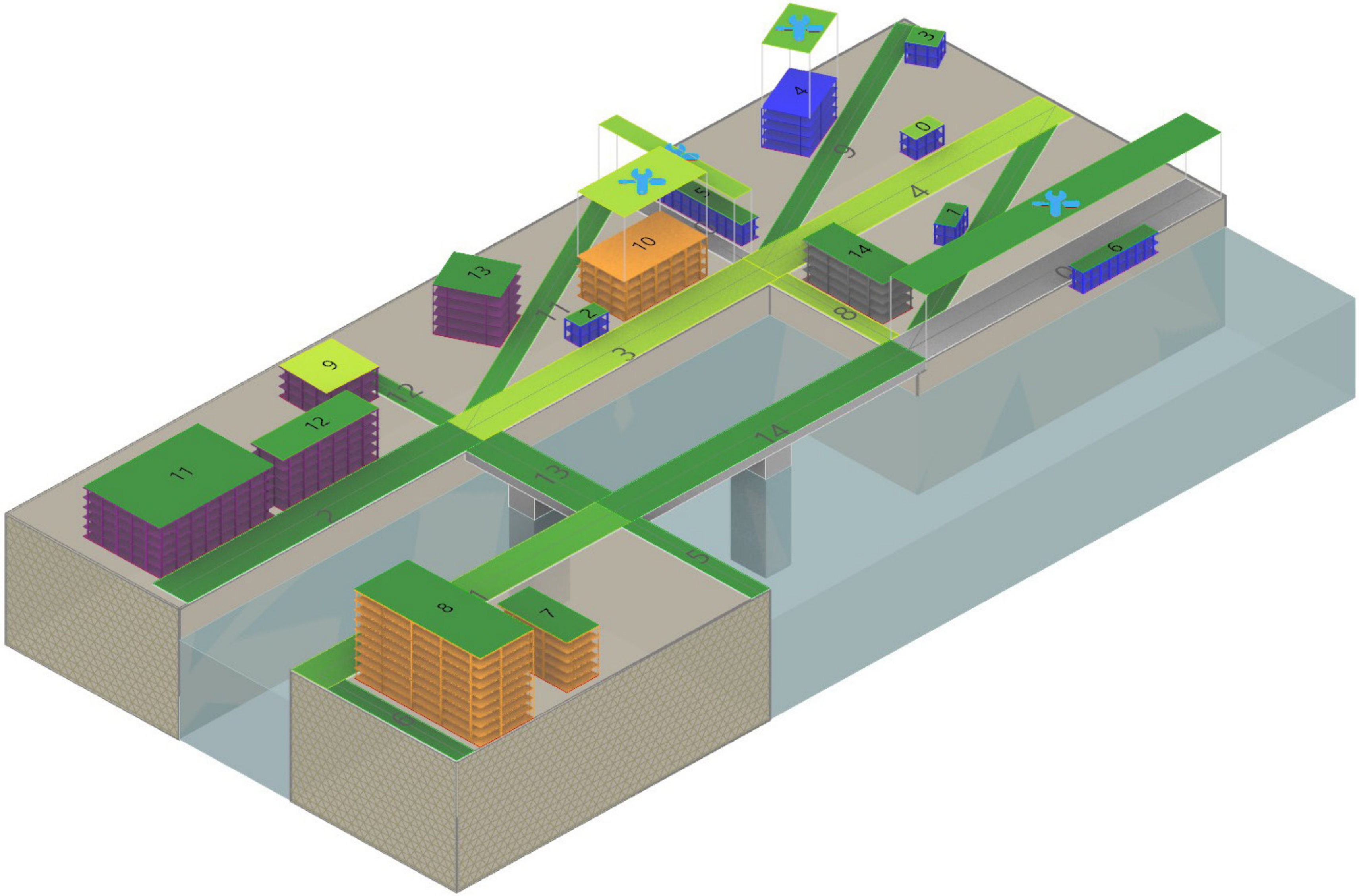
Context · Fragility · Recovery · Resilience · Traffic · Reinforcement Learning · Reward · **Experiment** · Conclusion

DCMAC

Repair time = 0 days

Repair time = 500 days

t = 14

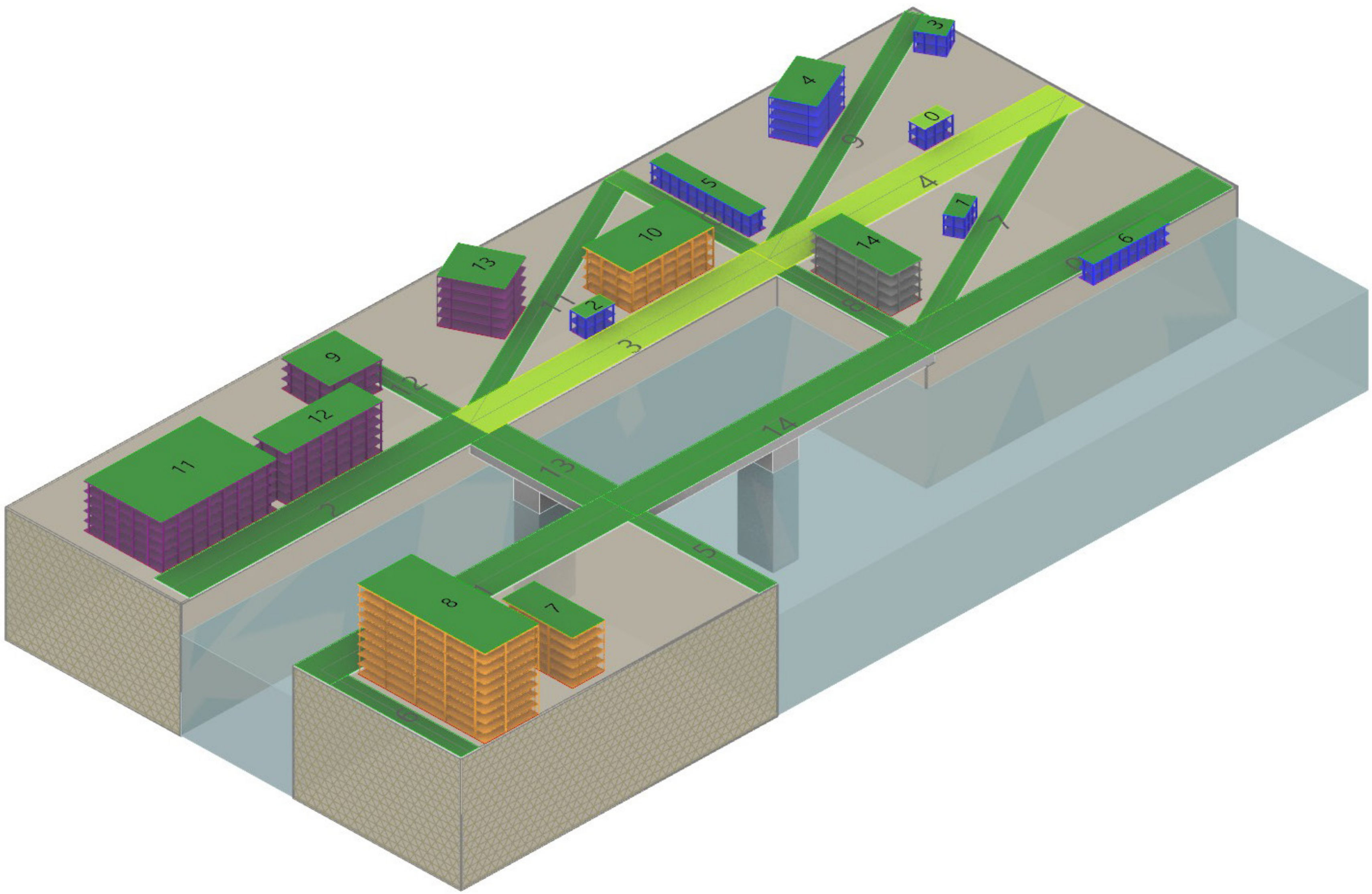


DCMAC

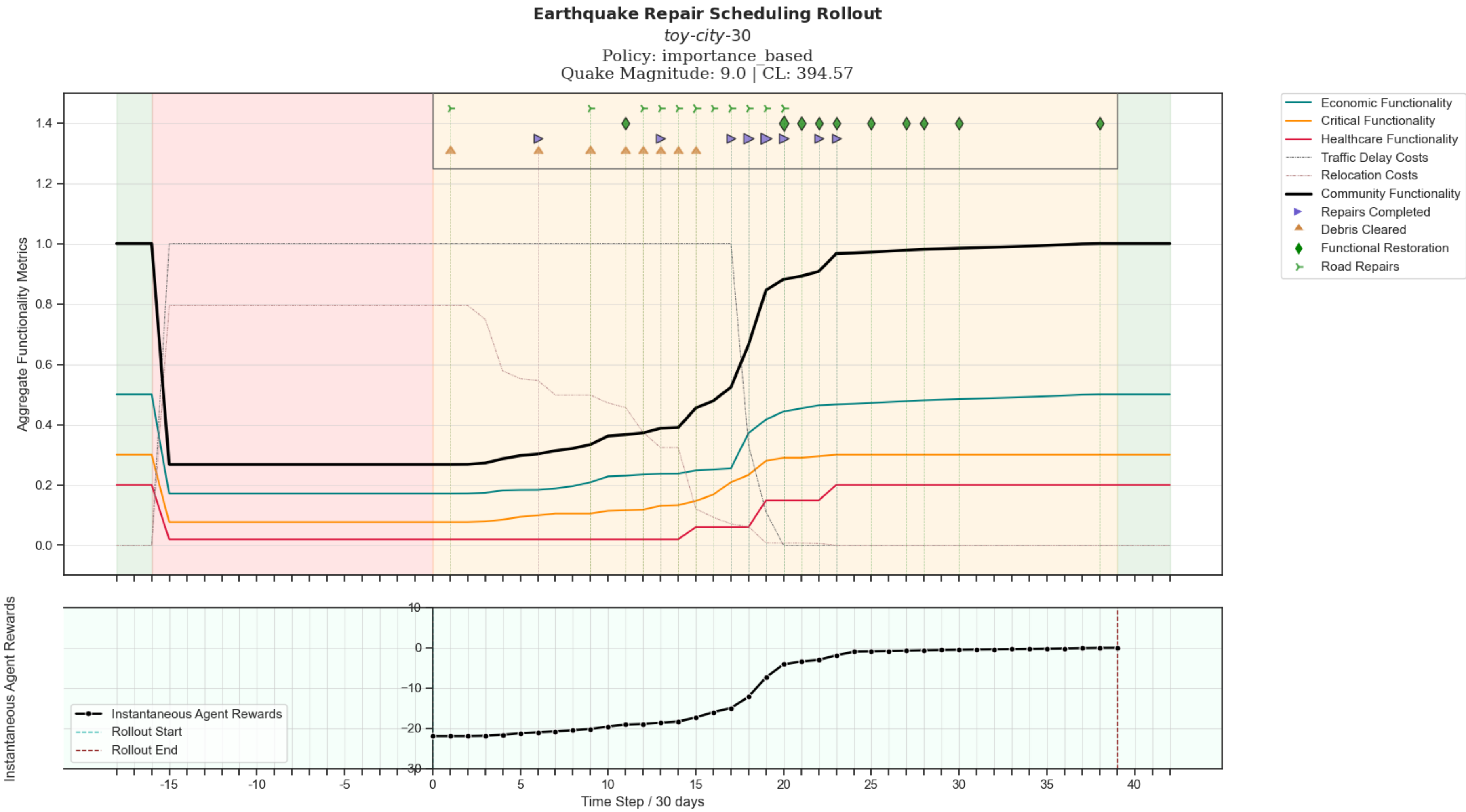
Repair time = 0 days

Repair time = 500 days

t = 100



Importance Based (IMPB)

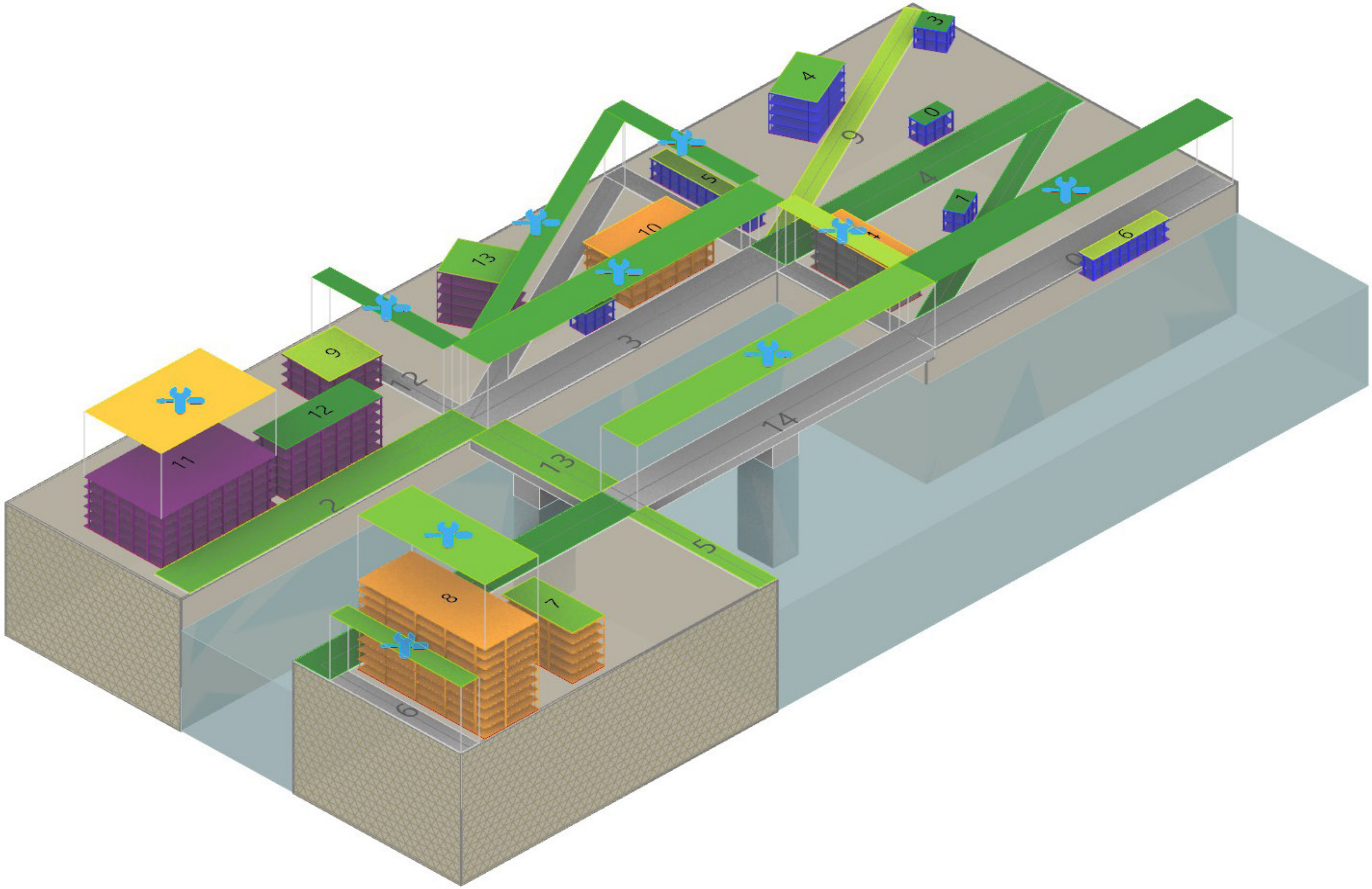


IMPB

Repair time = 0 days

Repair time = 500 days

t = 4

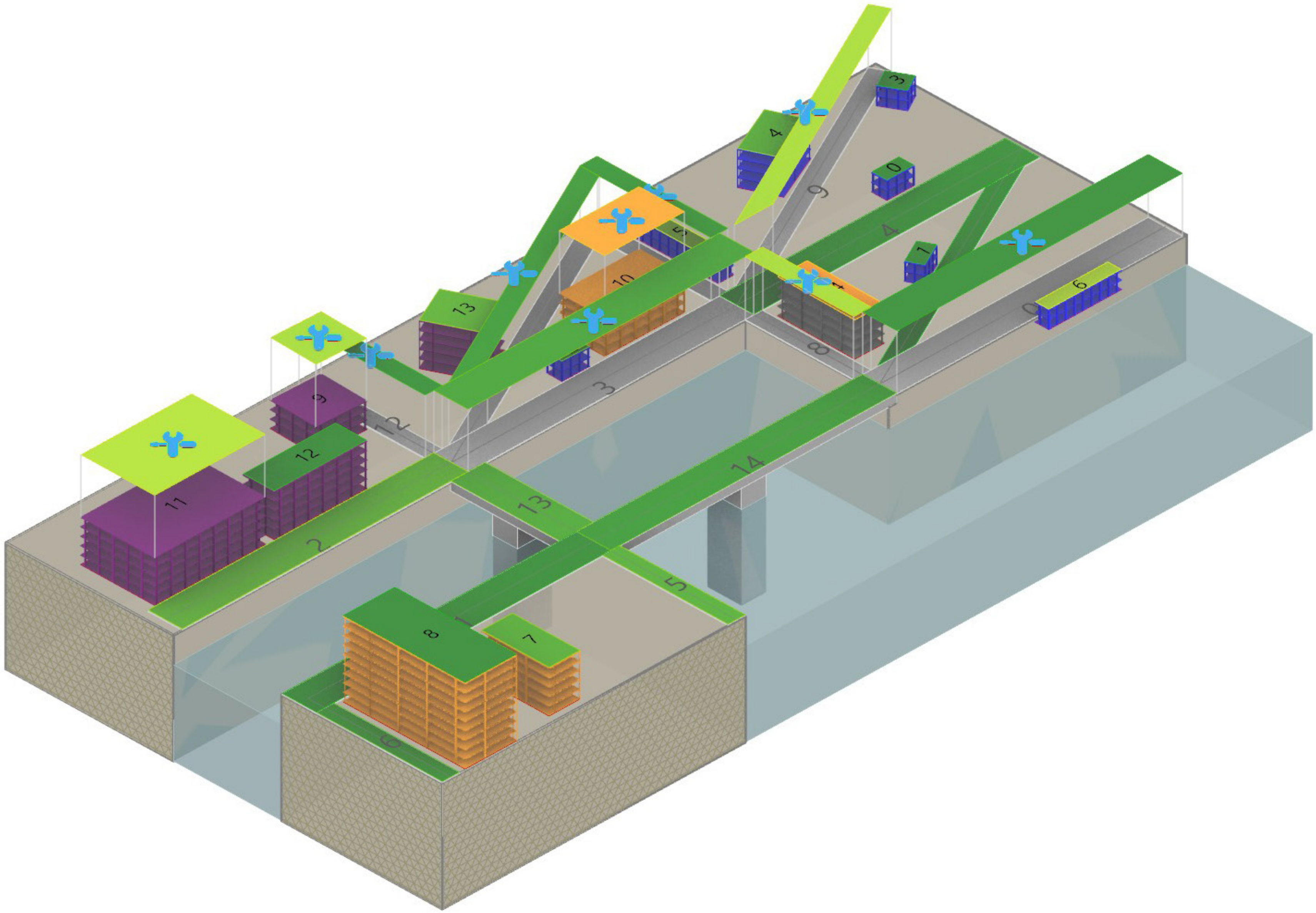


IMPB

Repair time = 0 days

Repair time = 500 days

t = 9

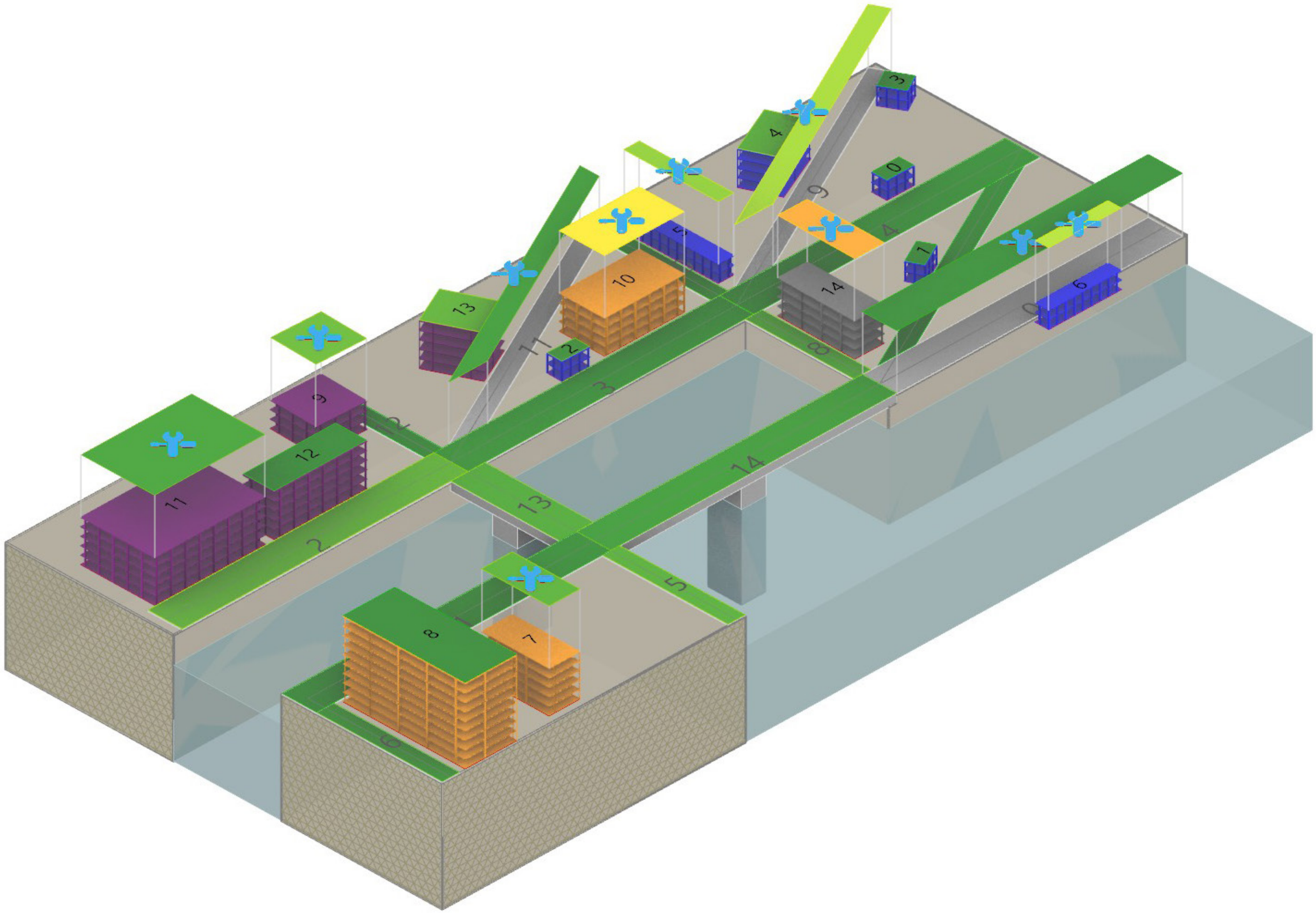


IMPB

Repair time = 0 days

Repair time = 500 days

t = 13

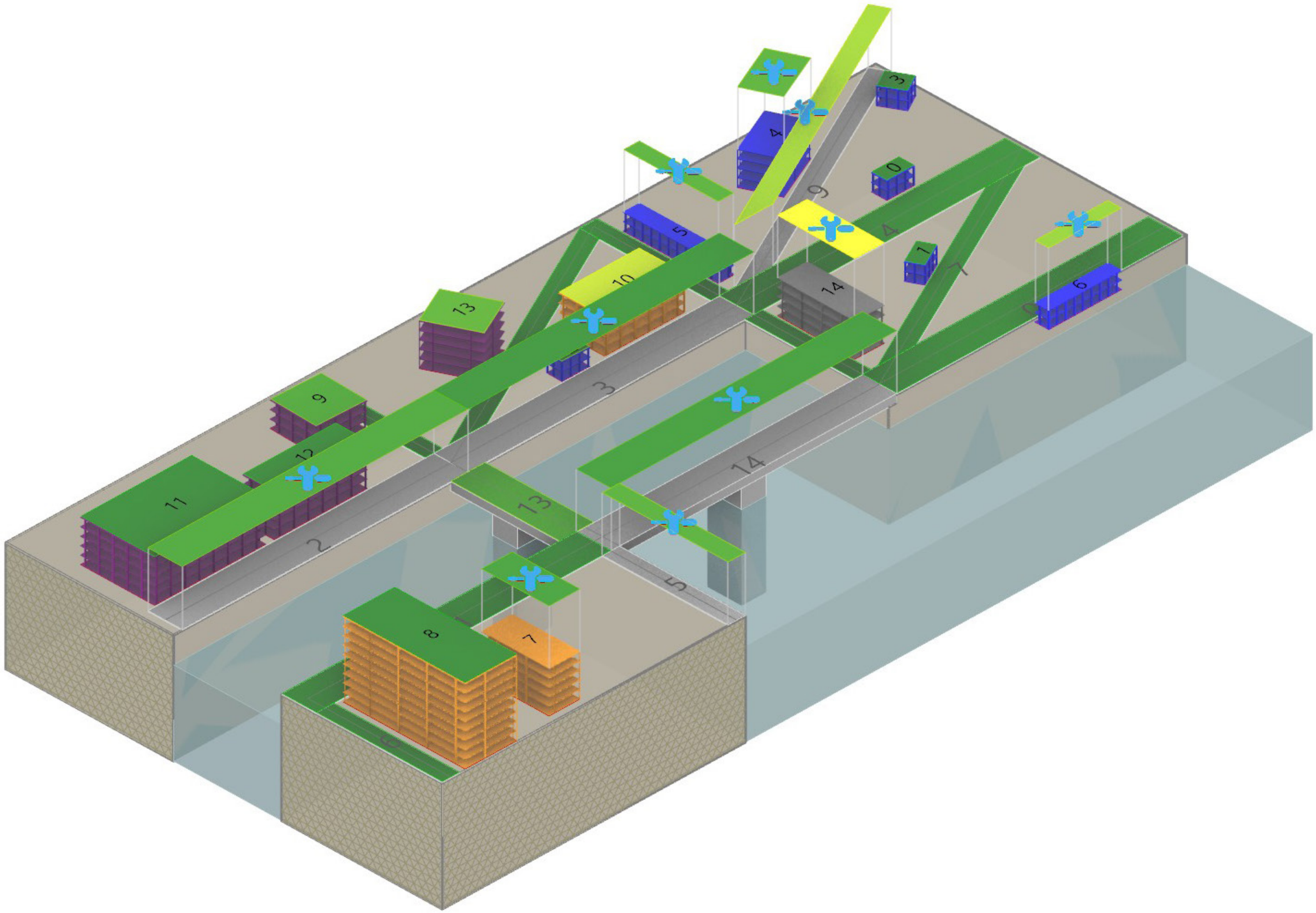


IMPB

Repair time = 0 days

Repair time = 500 days

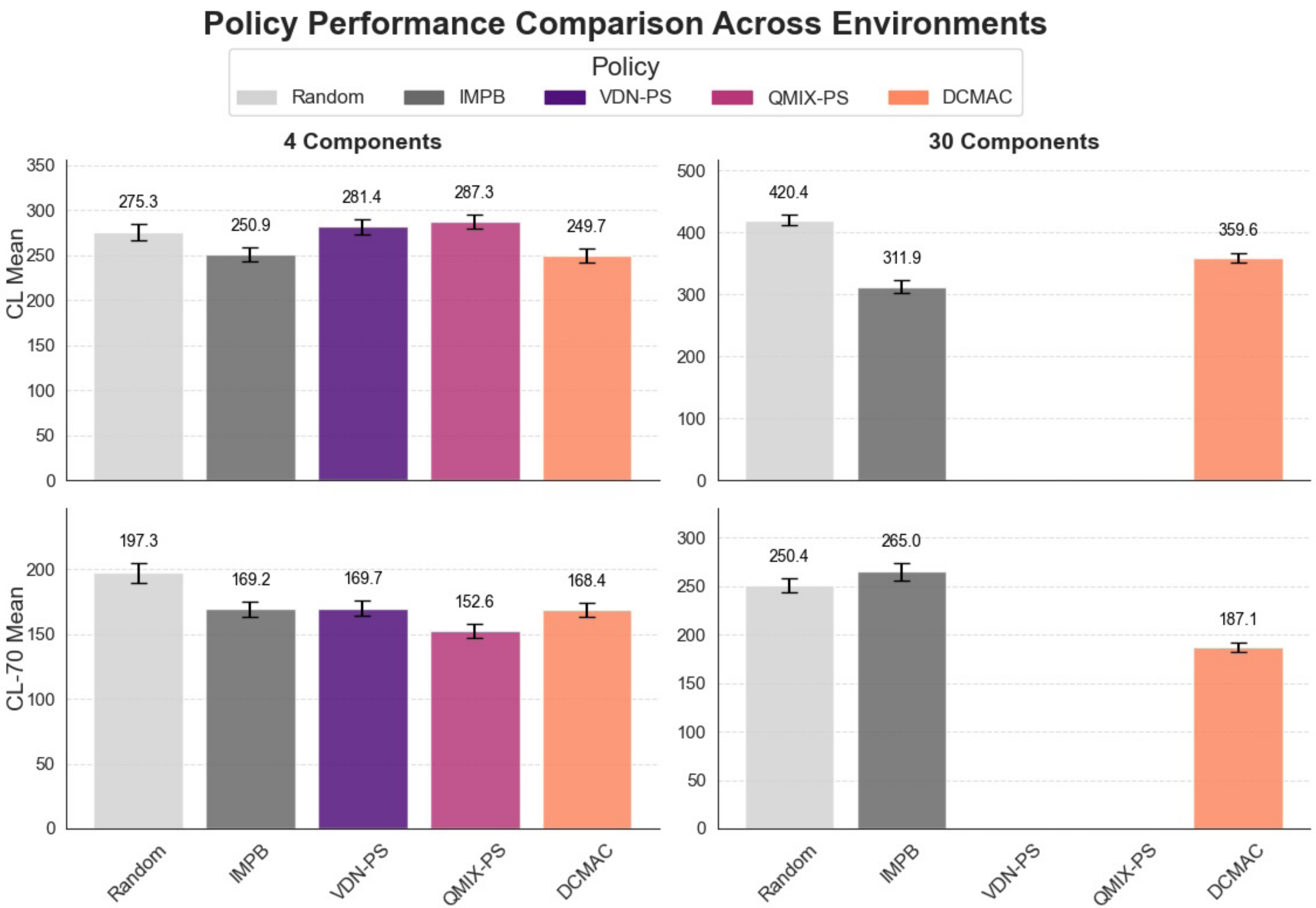
t = 16



Conclusions

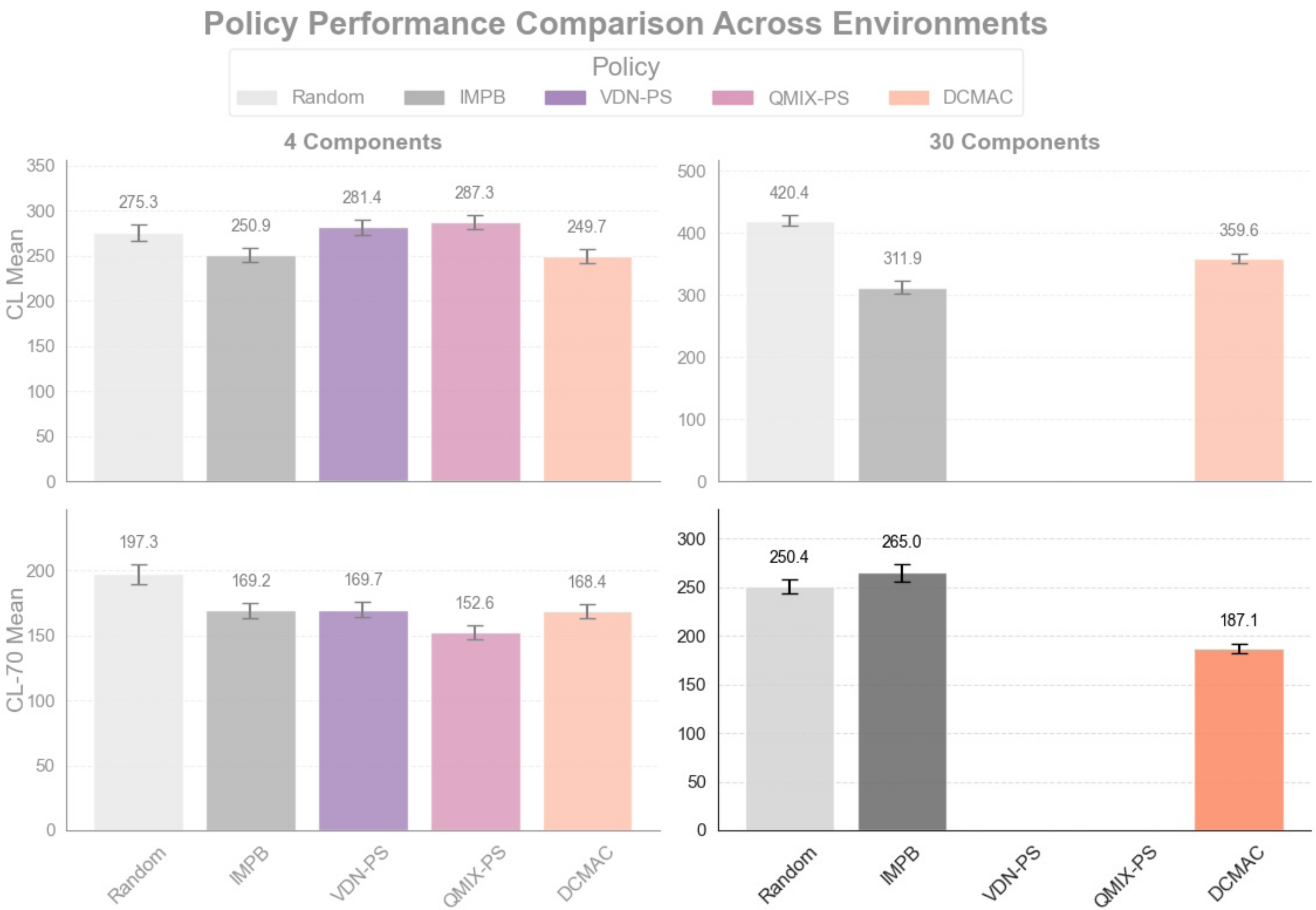
Work Presented

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



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



Q-RES MARL

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

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

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Invaluable assistance was also provided by Prateek Bhustali