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NATO CA2X2 Forum 2026

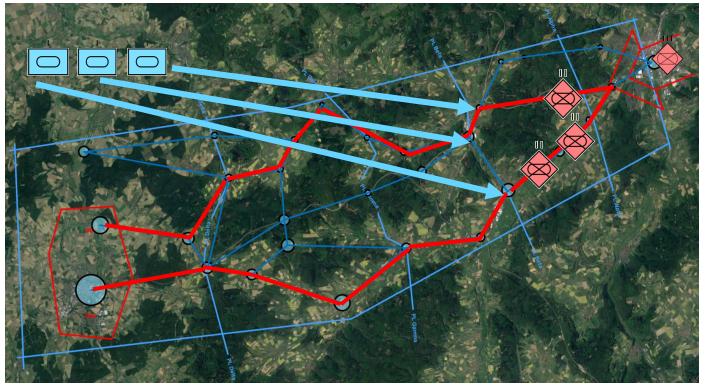
Graph Reinforcement Learning for Logistics Planning under Catastrophic and Adversarial Disruptions

Jonathan Cawalla, Marvin Gülhan, Lasse Ruttert, Hans-Christian Schmitz

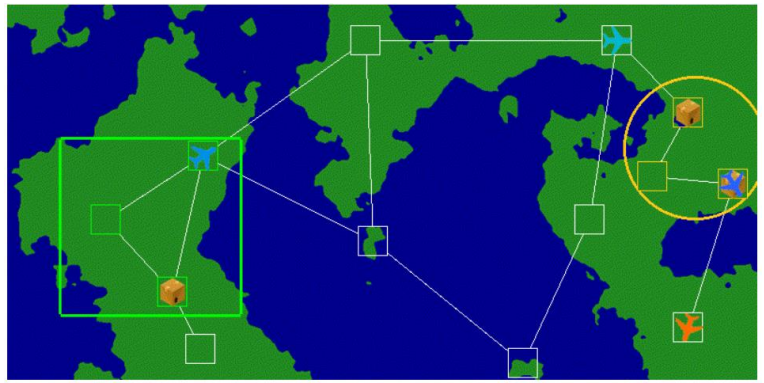
Introduction
Motivation

- Dynamic planning is crucial when adversaries or natural events disrupt one's plans.
  - **Disaster response and civil defense:** Disruptions caused by natural events or hostile actors.
  - **Military operations:** The adversary attempts to disrupt logistics and maneuver.

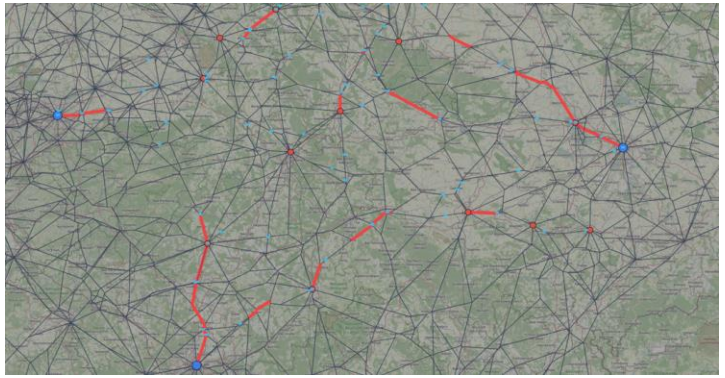
Network Disruption: CoA analysis



Dynamic Routing: Airlift Planning



Routing under Adversarial Disruption



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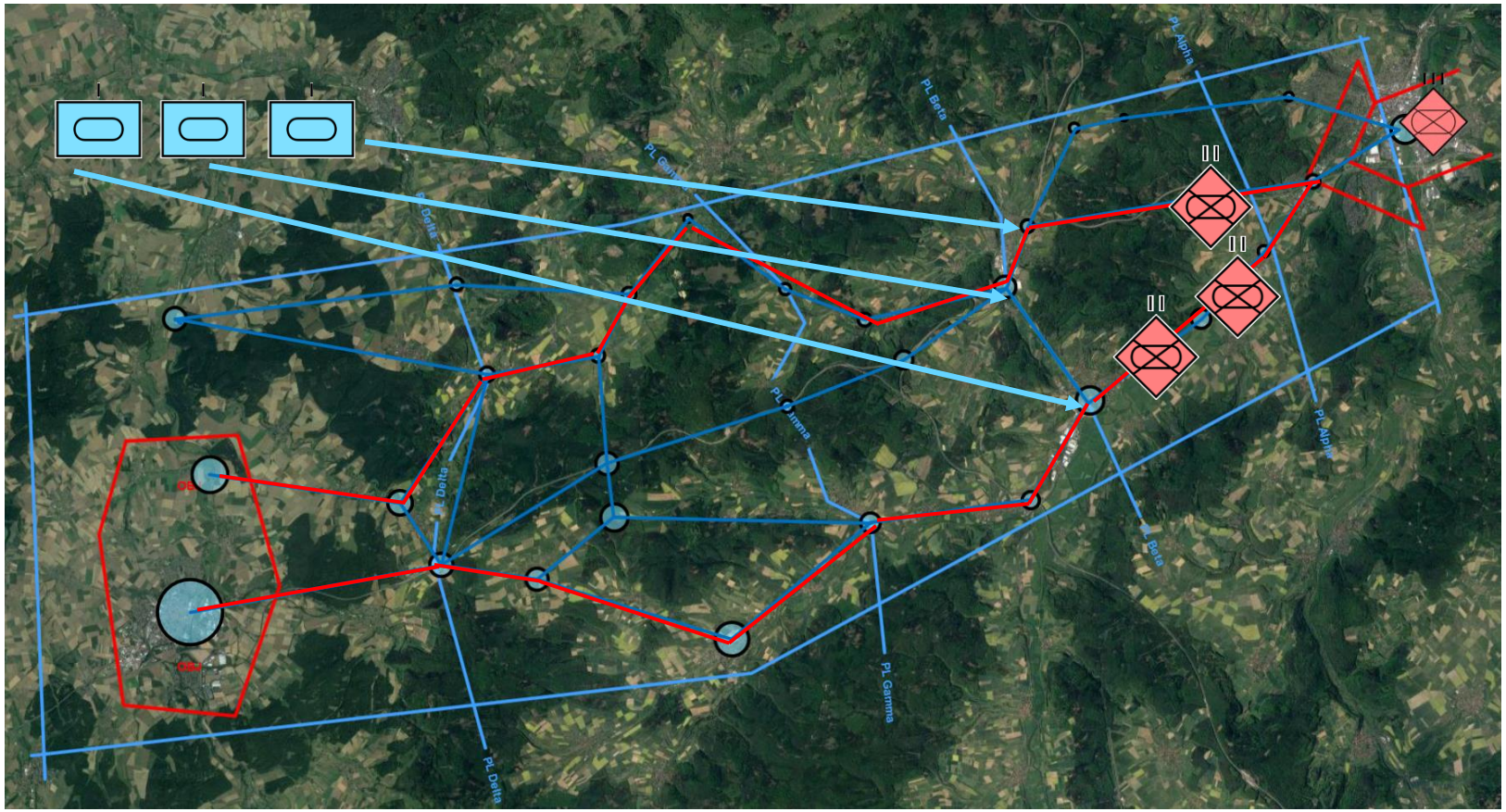
Network Disruption: Graph-based Analysis of CoAs

Concept



Goal: Identify areas where the deployment of own resources has the largest effect on stopping or delaying the red approach.

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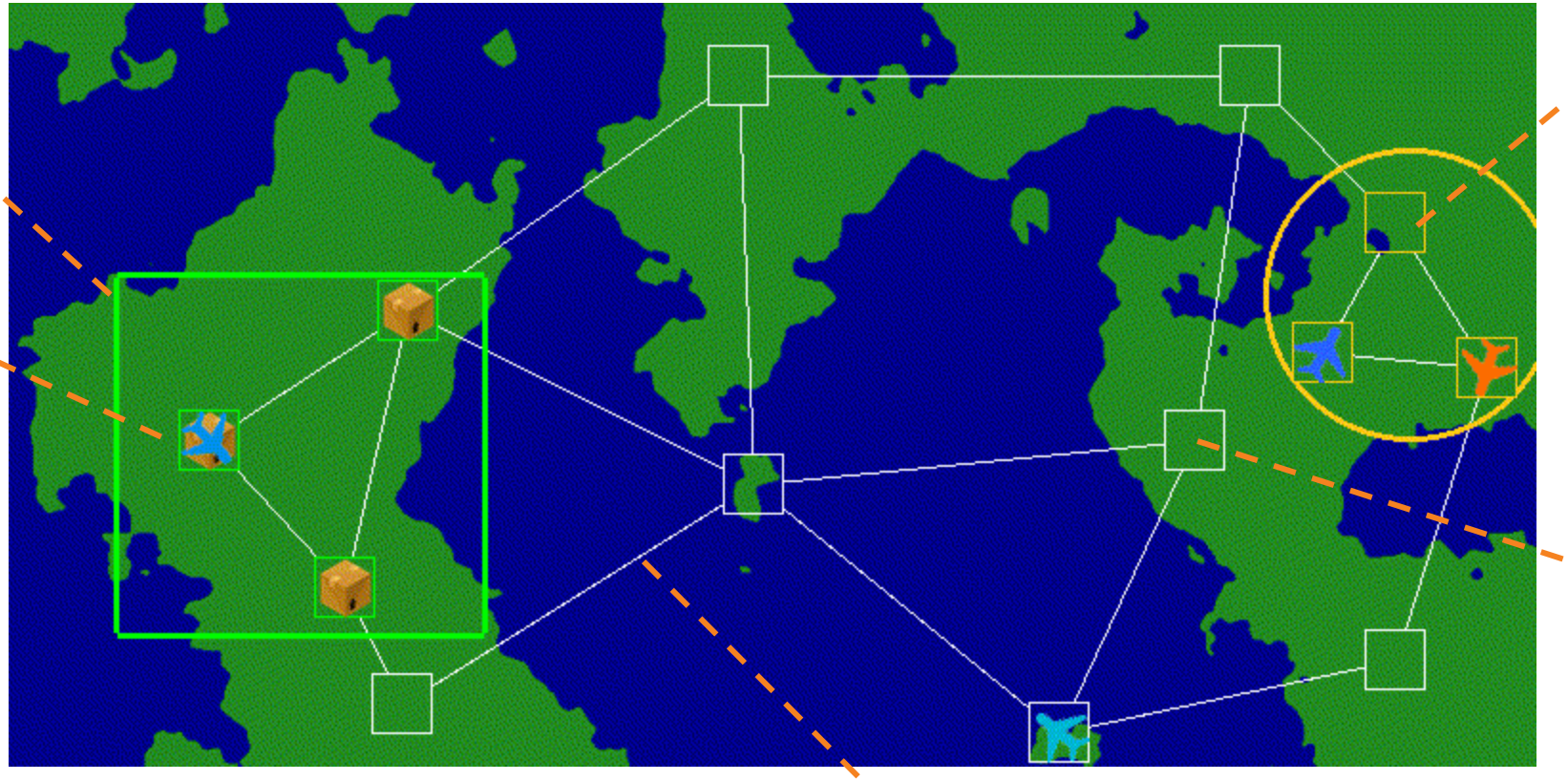
Dynamic Routing: **Airlift Planning Problem (APP)**

Objective: Deliver cargo items from pickup area to drop-off area using a fleet of aircraft

Pickup area

Dynamic cargo requests with time windows



Drop-off area

Nodes=Airports (with processing capacity)

Route malfunctions

Classical planning methods struggle in dynamic C2 environments

- **C2 environments are hard:** high complexity, operational constraints, uncertainty.
- **Conventional approaches:** optimization models, heuristics, and metaheuristics (Operations Research).

- **Problems:**
  - Exact optimization models become intractable due to runtime issues.
  - Hand-crafted heuristics need deep domain expertise and continuous tuning.
  - Changing requirements, which are common in military settings, requires costly re-engineering.

➔ These limitations motivate planning approaches that reduce manual modeling and adapt automatically

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Graph Reinforcement Learning (GRL)

- **Learning-based alternative:** Graph Reinforcement Learning (GRL).
- **Core idea:** instead of hand-crafting heuristics, learn them from a simulator via Reinforcement Learning (RL).
- **Related Work:** existing GRL work has focused mainly on classic optimization problems and classic routing problems, such as the Traveling Salesman Problem (TSP) and the Vehicle Routing Problem (VRP).
- **Research gap:** GRL for C2 planning, especially for dynamic graph-based multi-agent problems

Li et al. 2022, Cappart et al. 2023, Darvariu et al. 2024, Cawalla 2025.

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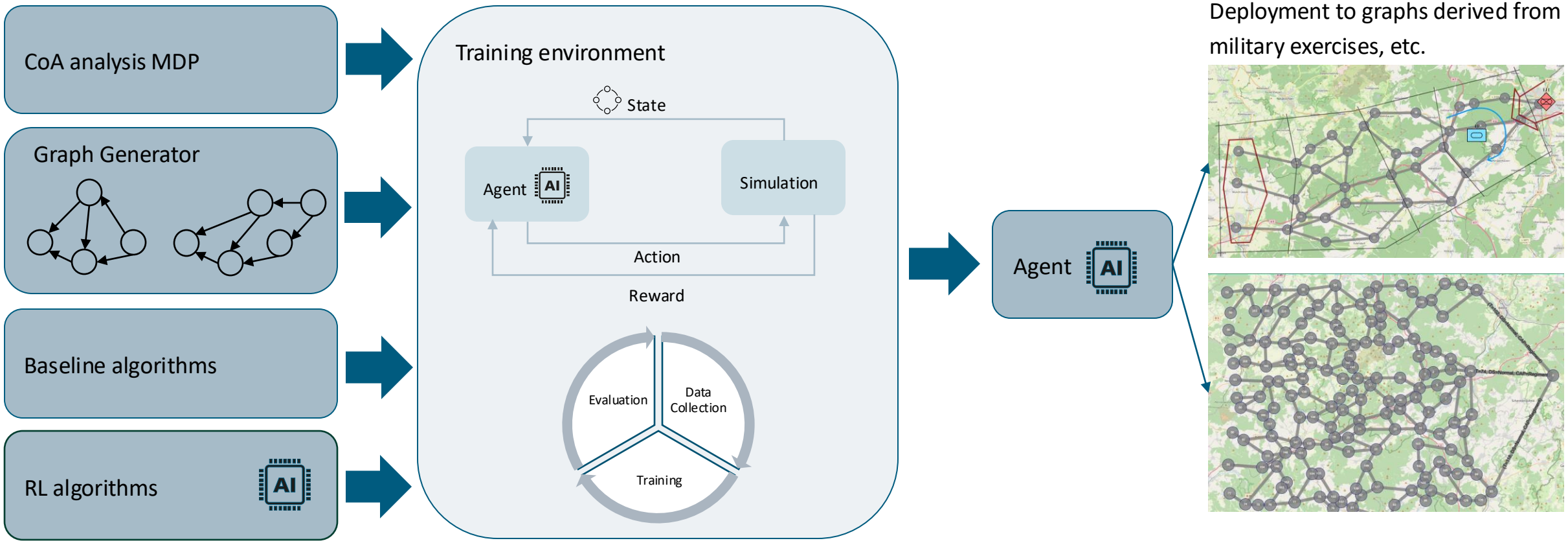
Reinforcement Learning Framework

Method



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Results so far

Disruption (CoA analysis)

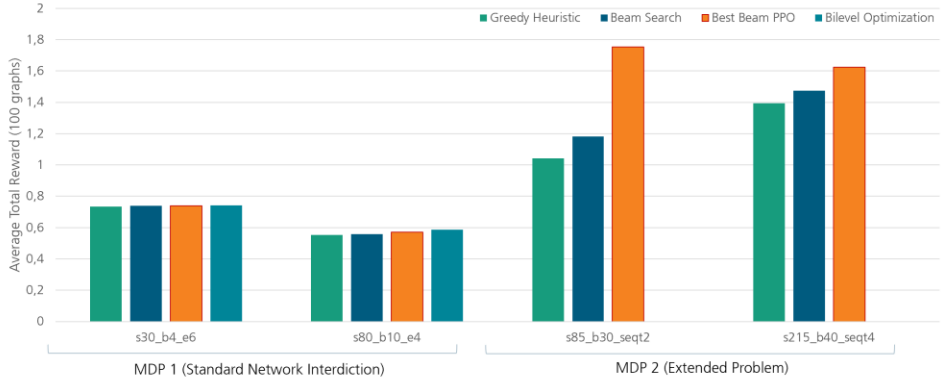
- Approach outperforms other heuristics
- Very close to classical optimization methods
- Applicable where optimization methods fail

Dynamic Planning (Airlift Planning)

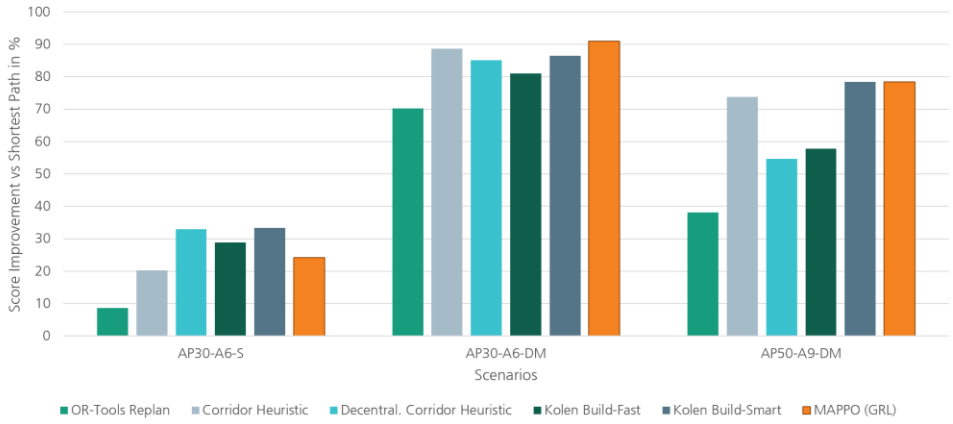
- A learned GRL policy matches or outperforms heuristics specifically designed for the problem, with the largest advantage in dynamic scenarios.

➔ GRL can reduce reliance on hand-crafted heuristics for dynamic, graph-structured planning problems.

Disruption Results (CoA analysis)



Dynamic Planning Results (Airlift Planning)



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Cawalla 2025, Cawalla & Gülhan 2026

Project “Logistics under Catastrophic Conditions” (Lokab)

Bundesamt
für Bevölkerungsschutz
und Katastrophenhilfe

Lokab:

- Funding from the German Federal Office of Civil Protection and Disaster Assistance (BBK)
- Project period: 2025–2027

Lokab focuses on optimizing logistics under challenging, dynamic conditions in the field of civil protection and disaster response.

Objective: Develop methods that use Reinforcement Learning to learn heuristics capable of handling these adverse conditions.

Problems:

1. Local crisis logistics: mass-casualty incidents (Dynamic Routing)
2. National crisis logistics: supply management and risk analysis (Dynamic Routing under Adversarial Disruption)

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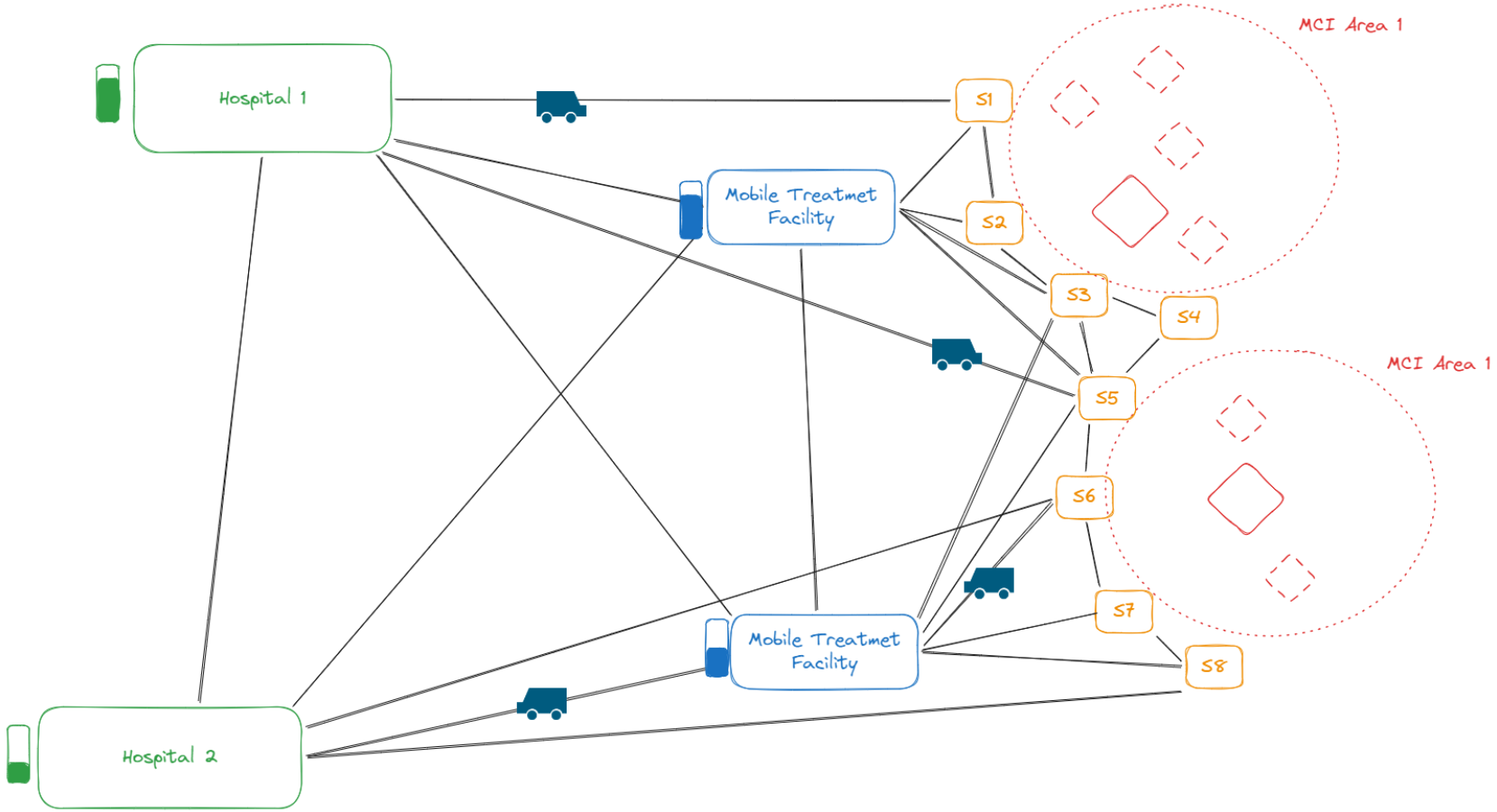
Dynamic Routing: Mass Casuality Incident

Problem Definition



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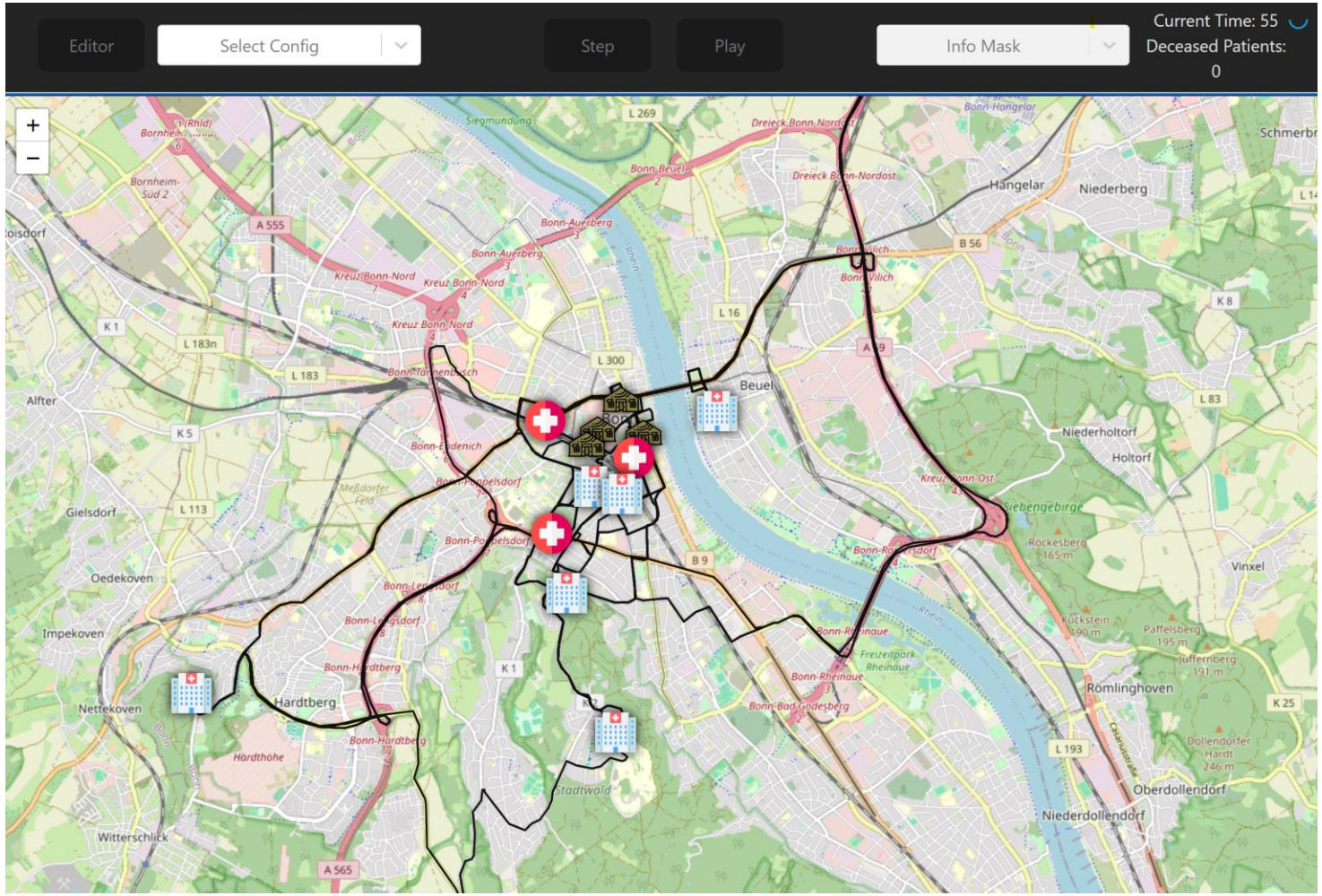
Dynamic Routing: Mass Casuality Incident

Demonstrator



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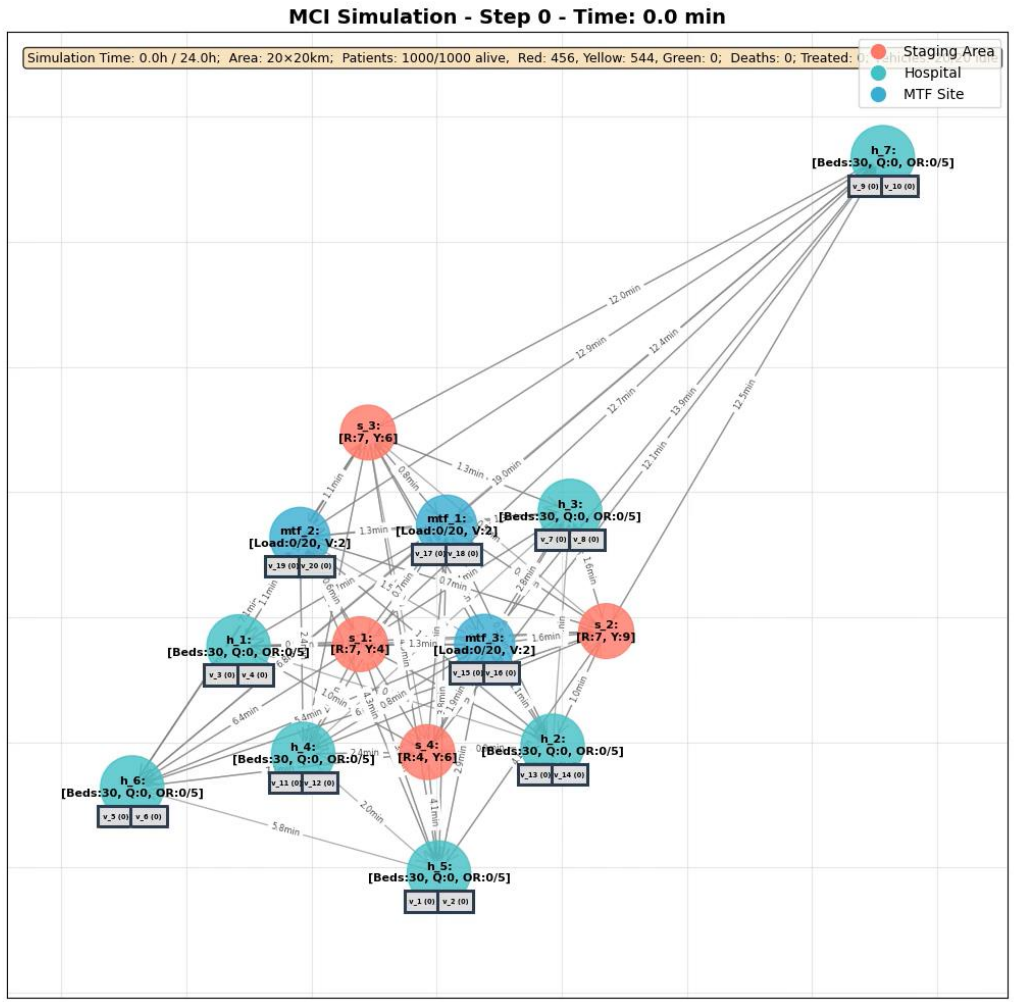
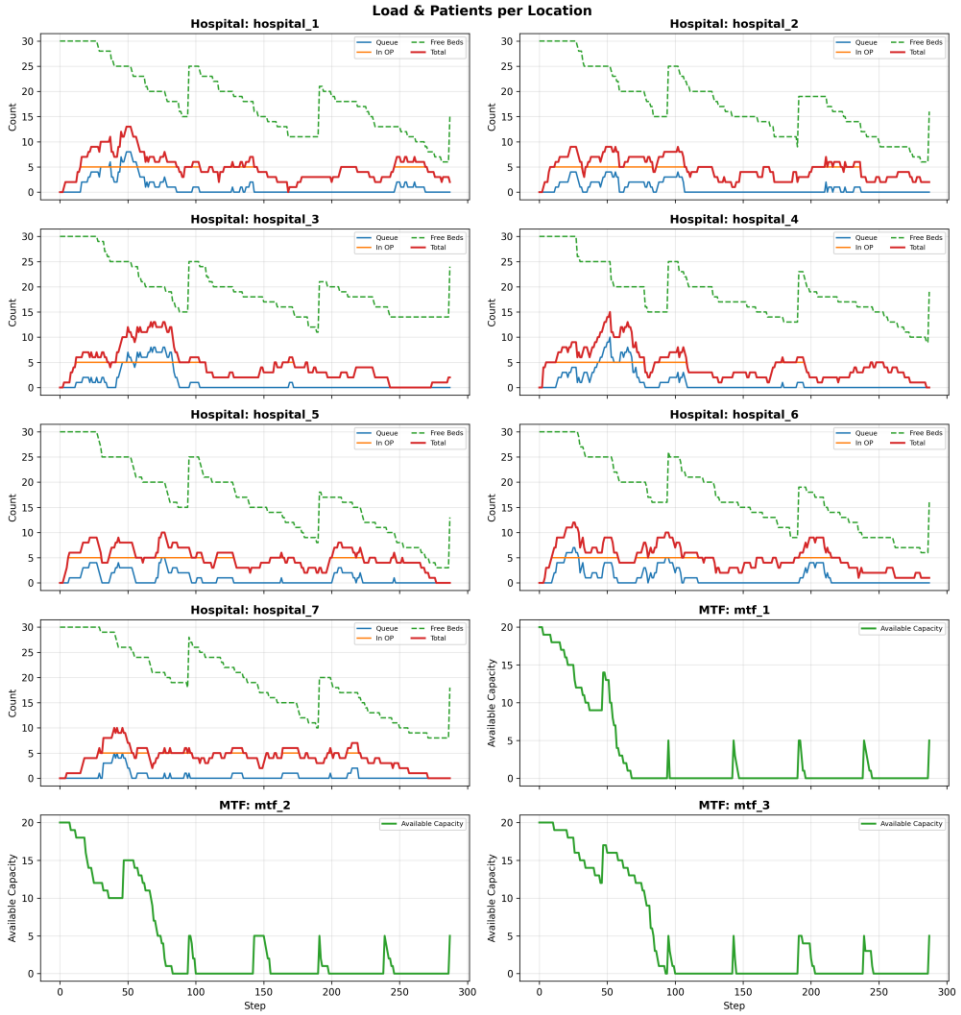
Dynamic Routing: Mass Casuality Incident





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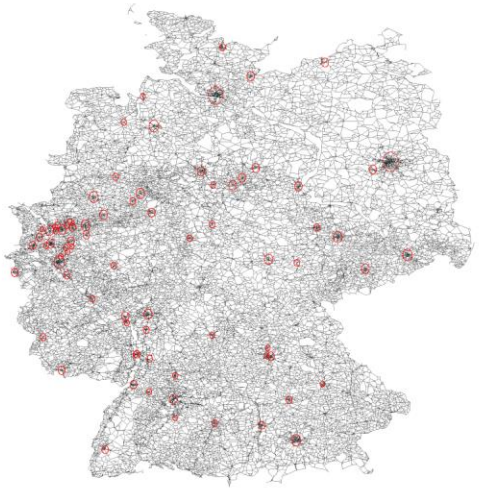
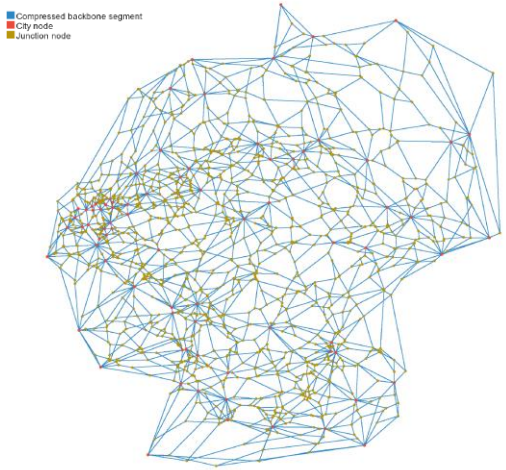
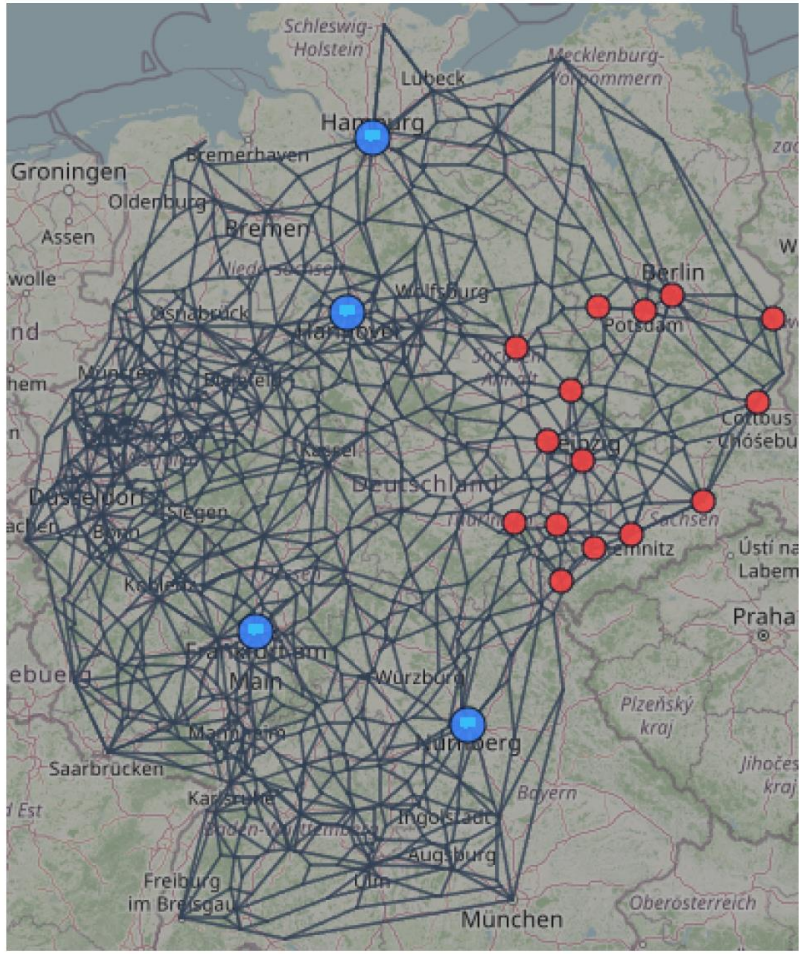
Dynamic Adversarial Routing: National Crisis Logistics

- **Objective:** supply the population with relief supplies (Focus of the civilian project Lokab)
- **Military perspective:** supply an area of operations with required materiel







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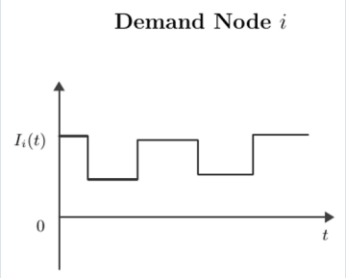
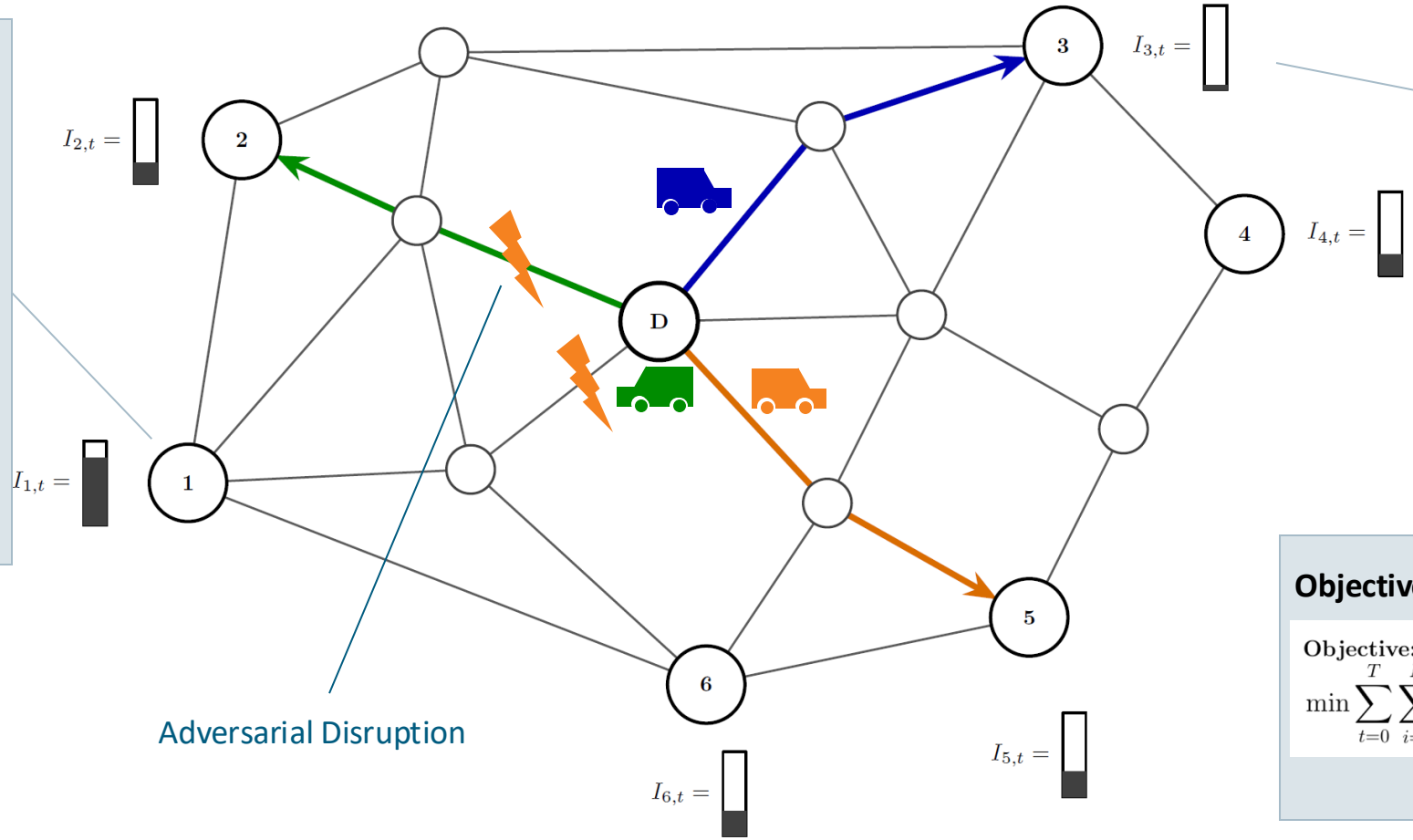
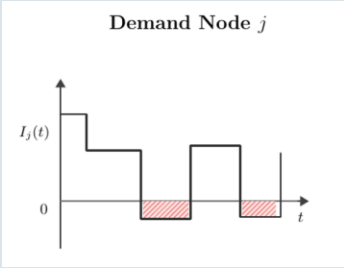
Problem Definition: Inventory Routing under Adversarial Disruption

Demand node inventory



Goal: demand nodes have always enough supply





Problematic case: multiple Stockouts

Objective function

Objective: minimize cumulative shortage

$$\min \sum_{t=0}^{T} \sum_{i=1}^{N} \left[-I_i(t)\right]_+$$

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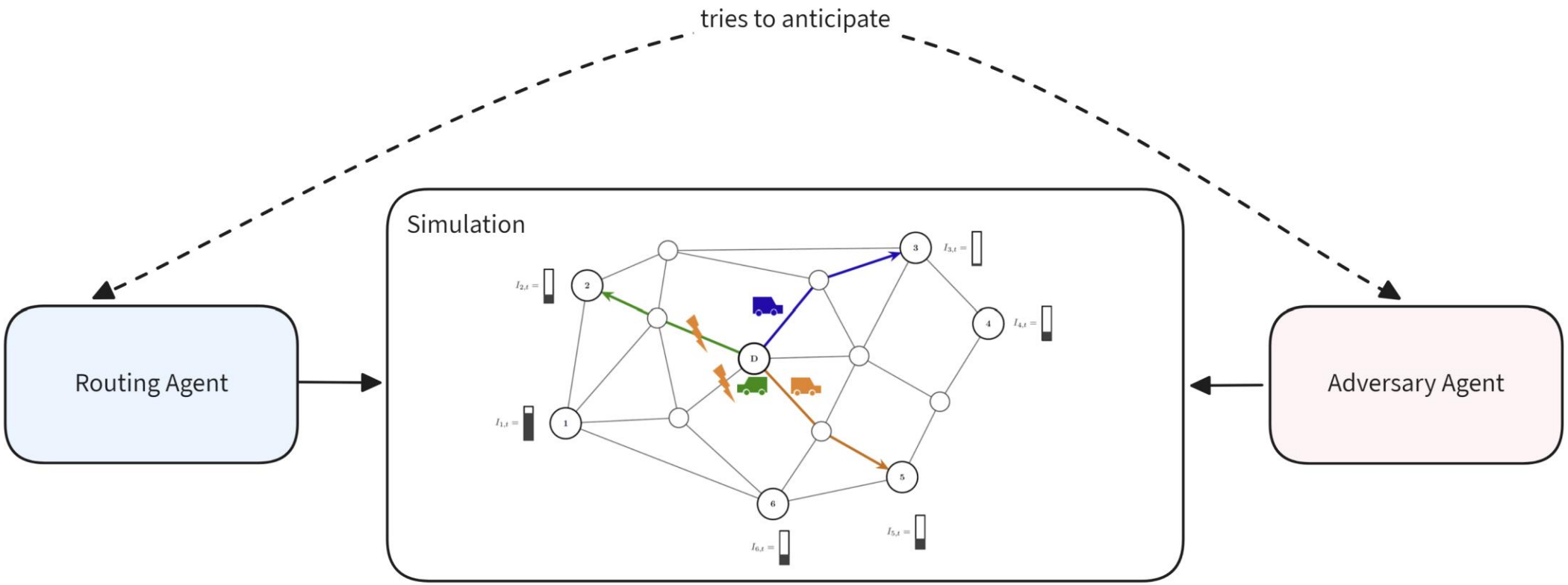
Routing Agent and Adversary Agent



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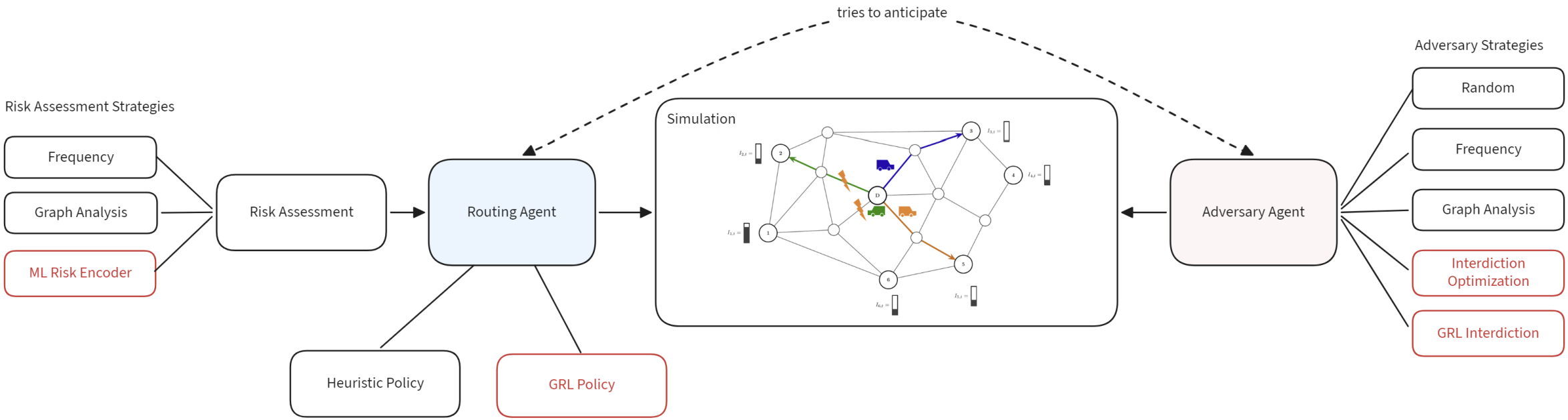
Agent Strategies



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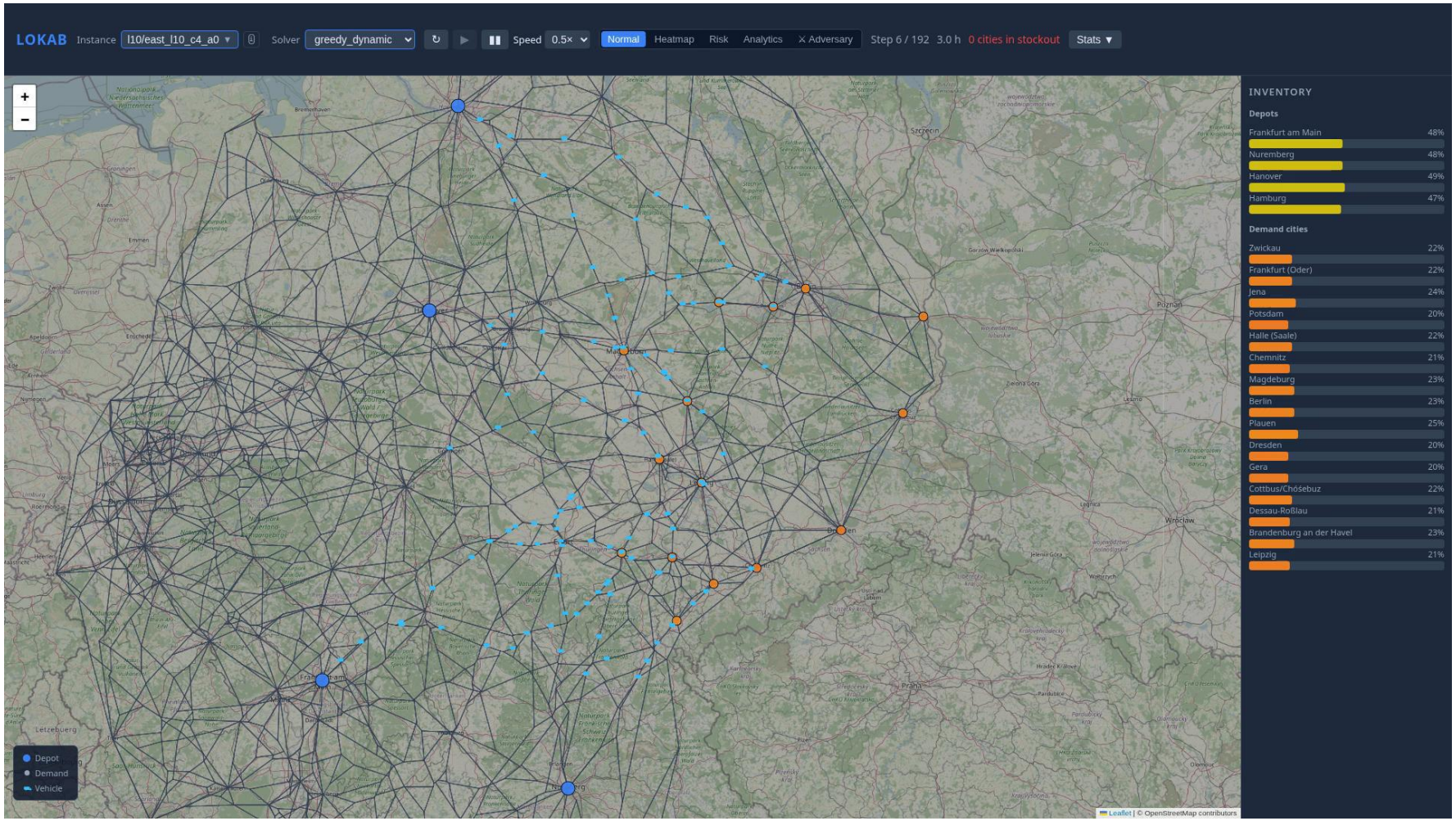
Outlook: Risk Assessment

Transport Flow without Disruptions



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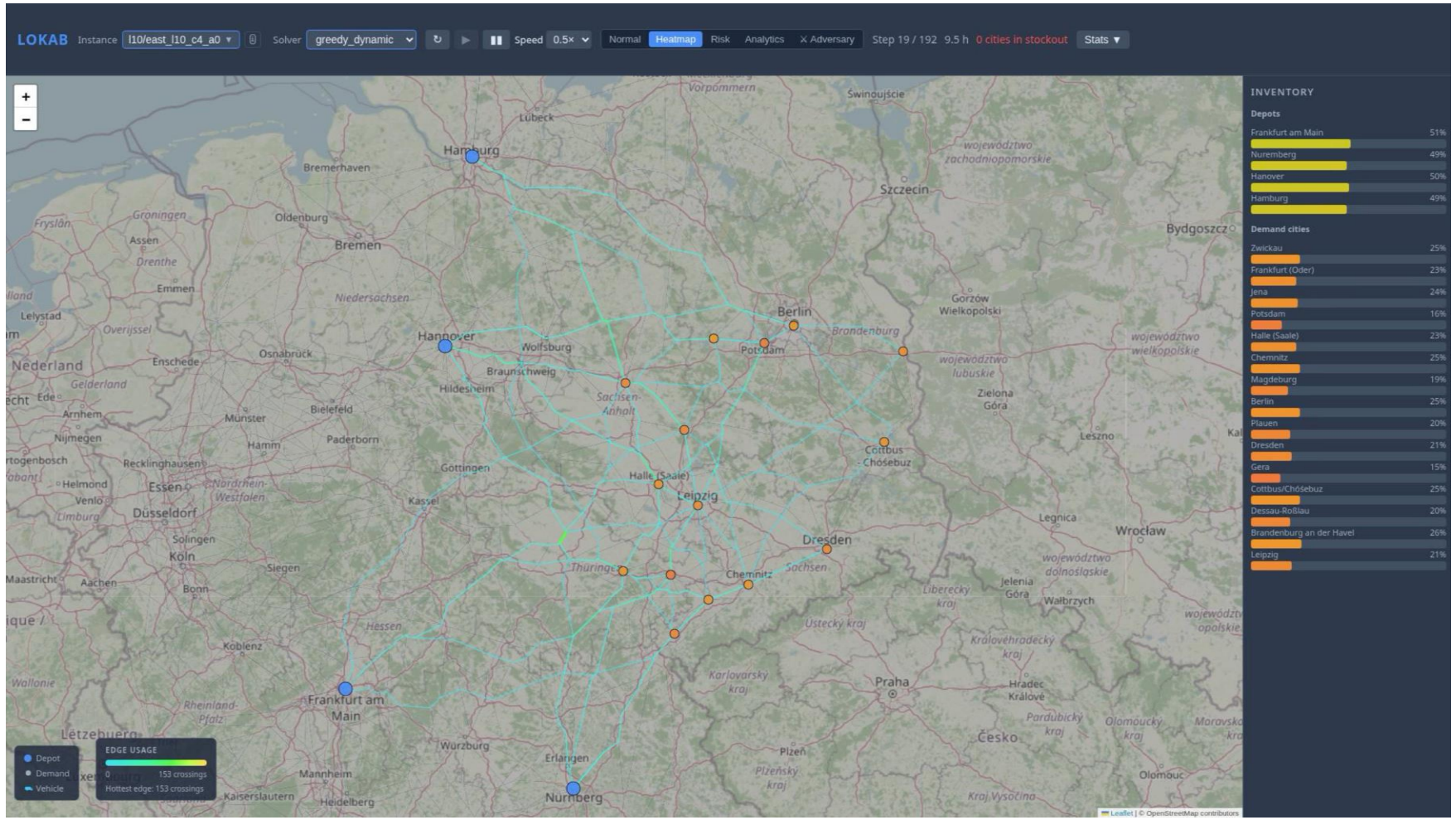
Outlook: Risk Assessment

Important Corridors Heatmap



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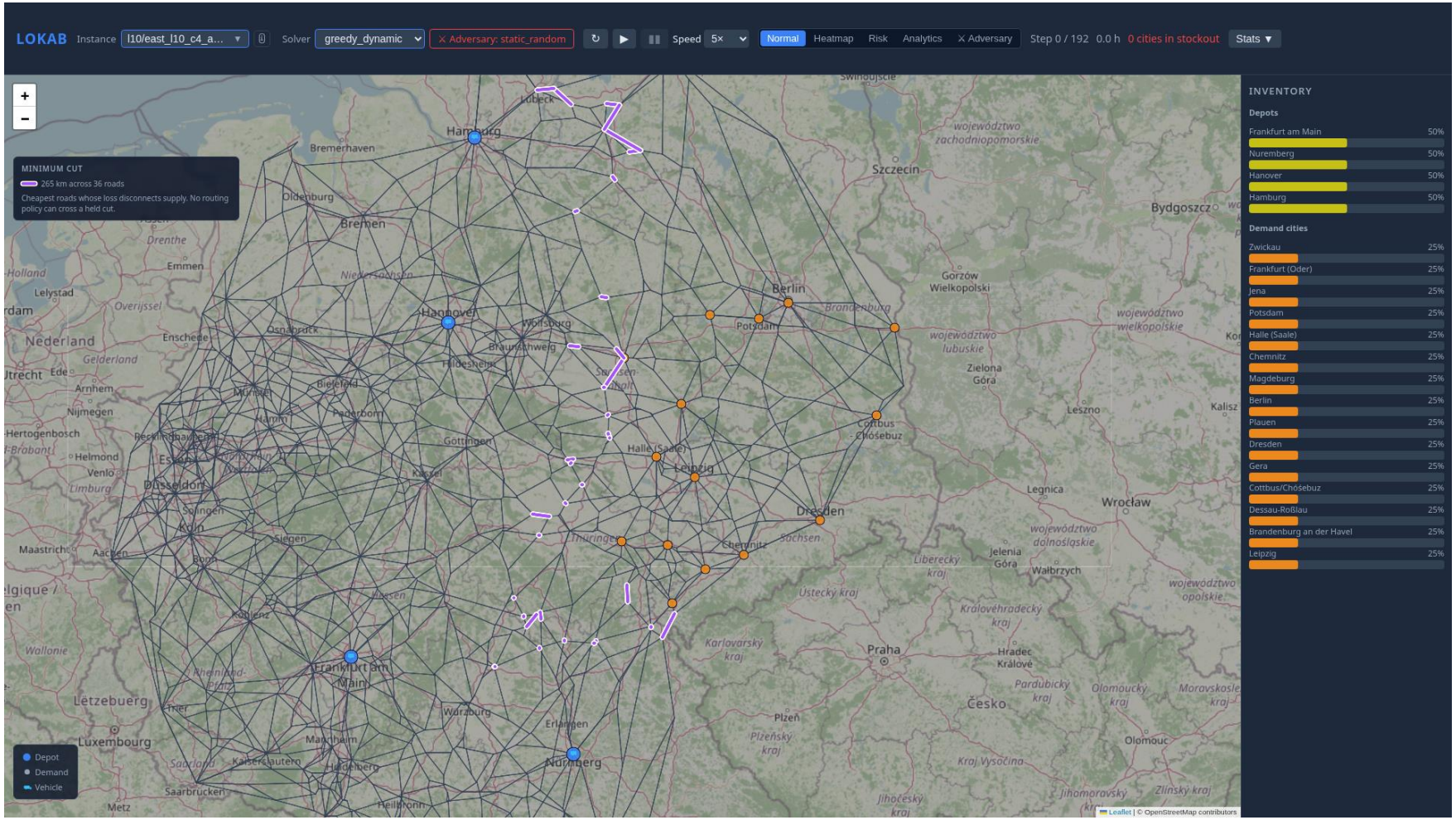
Outlook: Risk Assessment

Min-Cut Disruption



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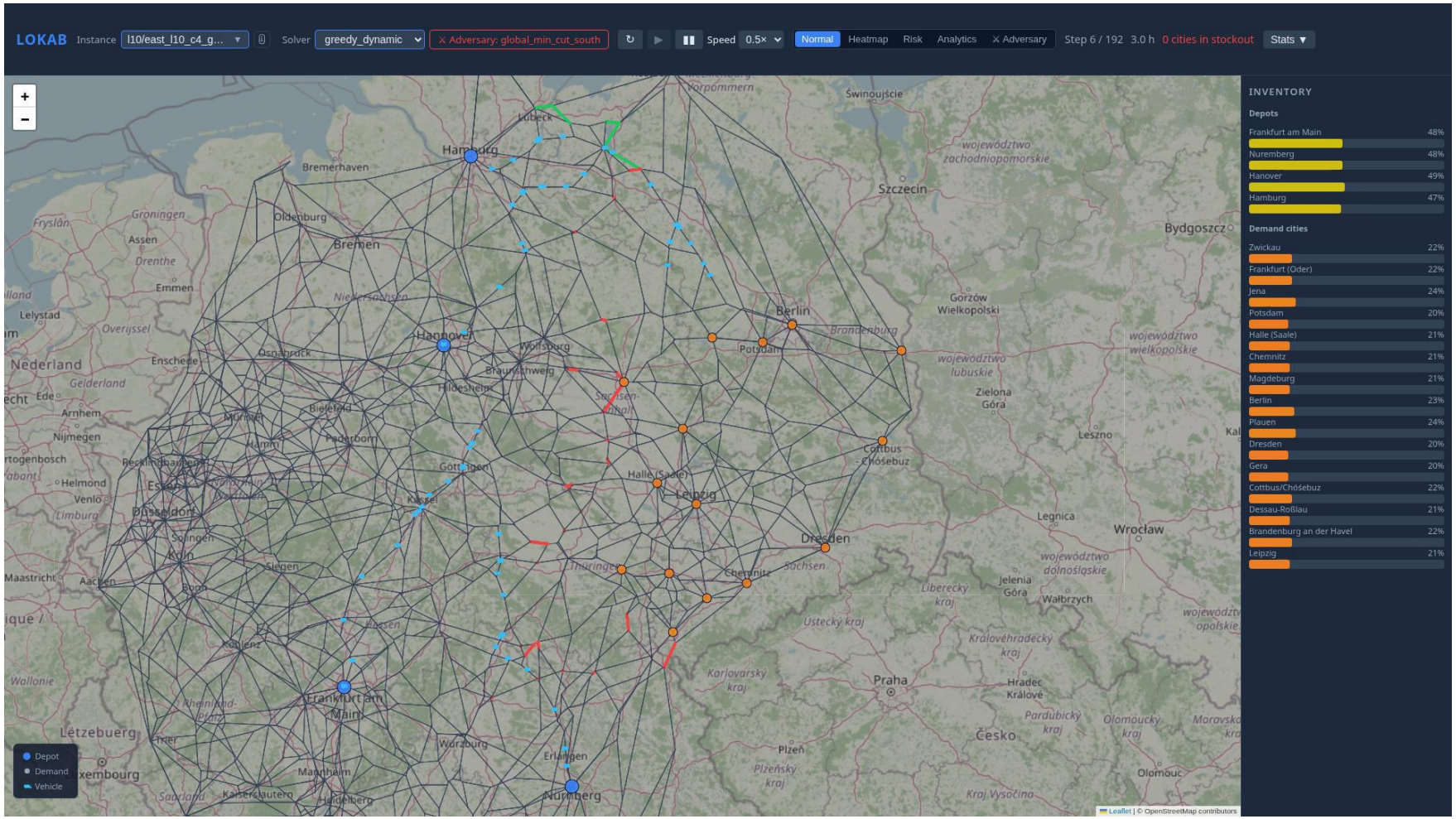
Outlook: Risk Assessment

Transport Flow with active Min-Cut Adversary



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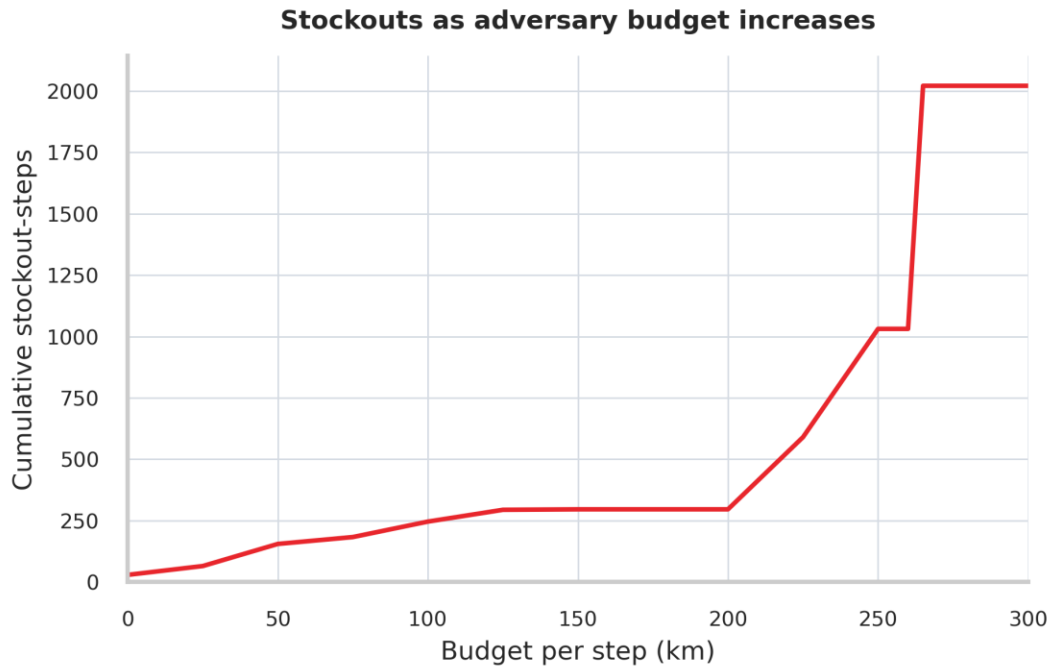
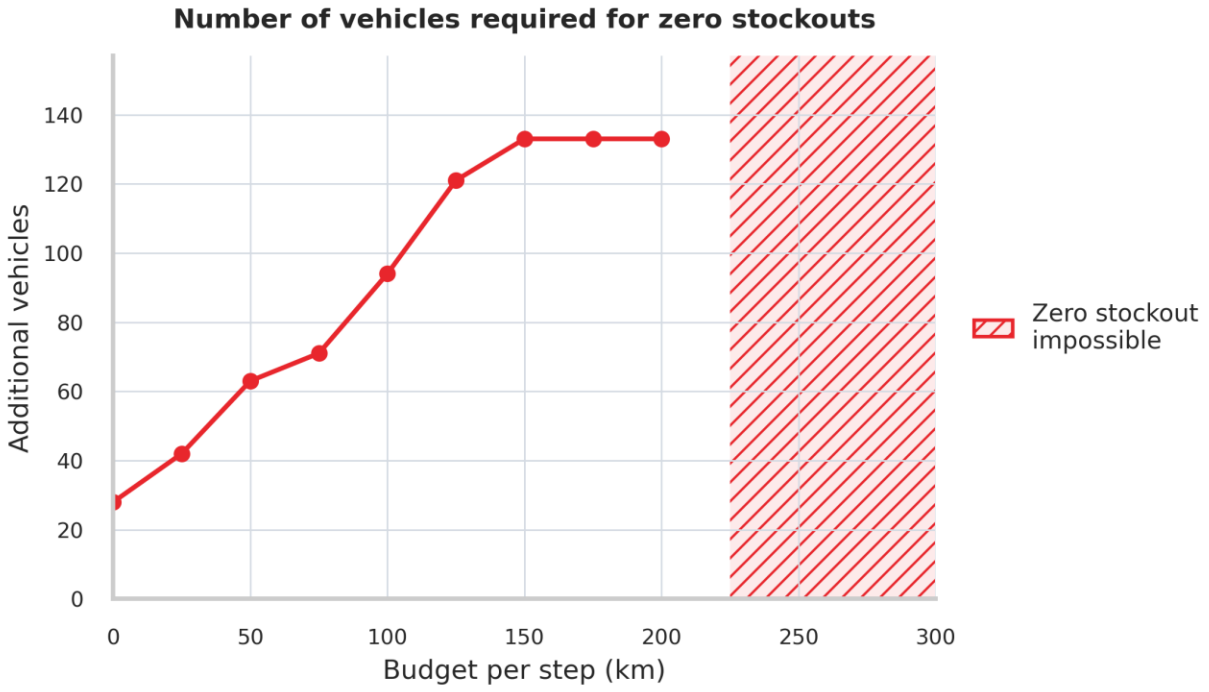
Outlook: Risk Assessment

Transport Flow with active Min-Cut Adversary





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Summary & Outlook

- A learned GRL policy can often match or outperform other methods specifically designed for the problem.
- This advantage is especially important in C2 environments and problems where requirements change, and dynamic and adverse situations are the norm.

- Future Work:
  - Further improving GRL methodology (Multi-Agent approaches, Centralized vs Decentralized, Adversary Prediction).
  - Scaling GRL to larger and more diverse graphs.
  - Exploiting analogies between civilian and military planning problems as well as risk assessments.

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