A Network Science and System Dynamics Simulation Framework for Installation Resilience under Compound Extremes

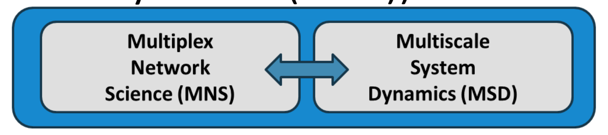
US Naval Research Laboratory: Dr. Satish Chikkagoudar (Satish.Chikkagoudar.civ@us.navy.mil)
Pacific Northwest National Laboratory: Dr. Samrat Chatterjee, Dr. Dennis Thomas
Northeastern University: Dr. Auroop R Ganguly

SERDP DOD · EPA · DOE
RC20-1183

Summary

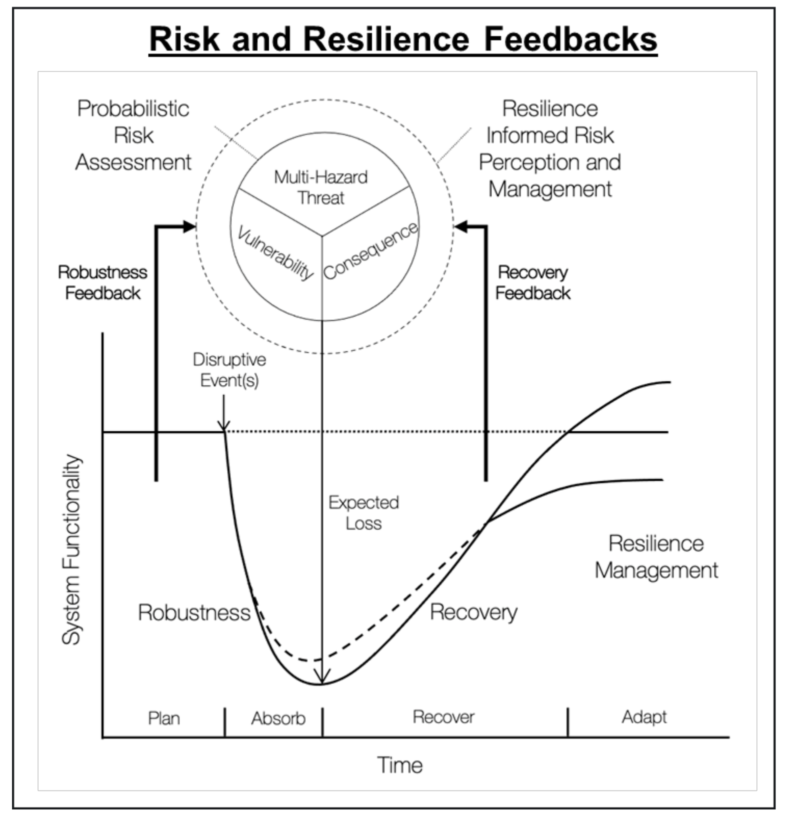
Problem: U.S. Department of Defense (DoD) installations face external compound threats from a combination of natural and man-made hazards. The growing interdependence of networked assets, within and around an installation, further lead to the possibility of cascading failures. Ensuring installation mission readiness and resilience under such conditions with scarce resources is a challenging problem. Resilience Encapsulates Principles of Risk, Robustness, and Recovery. One needs to address system complexities, dependencies, heterogeneities, and dynamics in order to model installation resilience.

Objective: Represent and implement installation resilience framing and modeling through multiplex networks (Multiplex Network Science (MNS)) complemented by system dynamics (Multiplex System Dynamics (MSD)).



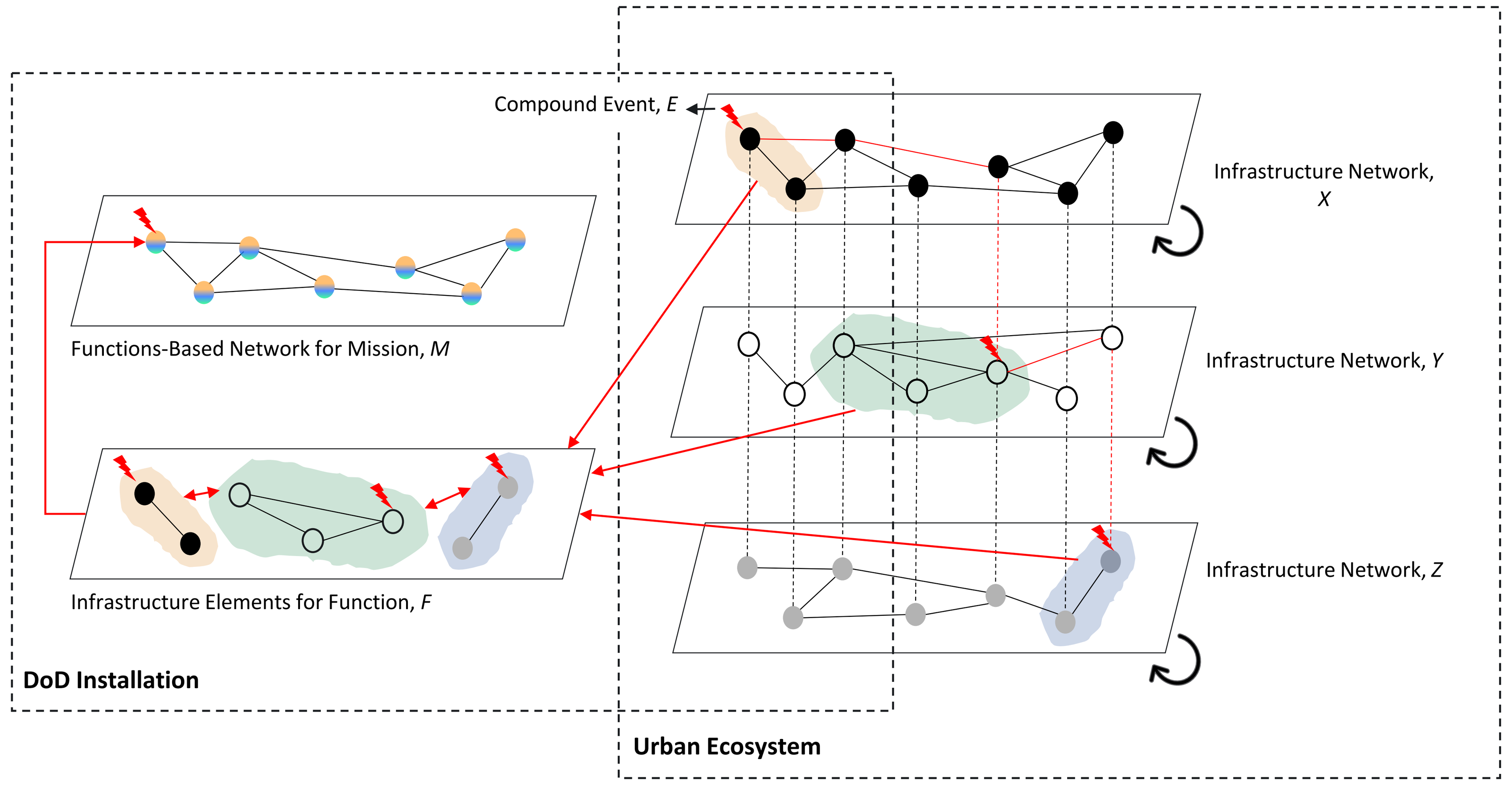
Research Hypotheses

- A combination of system dynamics with network science can enable resilience framing for compounding and potentially unknowable risks
- Resilience and mission assurance can be ensured even without comprehensive knowledge of the specific nature of compounding threats or risks
- Recovery of mission critical functionality can be accomplished via complementary strengths of network multiplex and system dynamics in conjunction with human experts



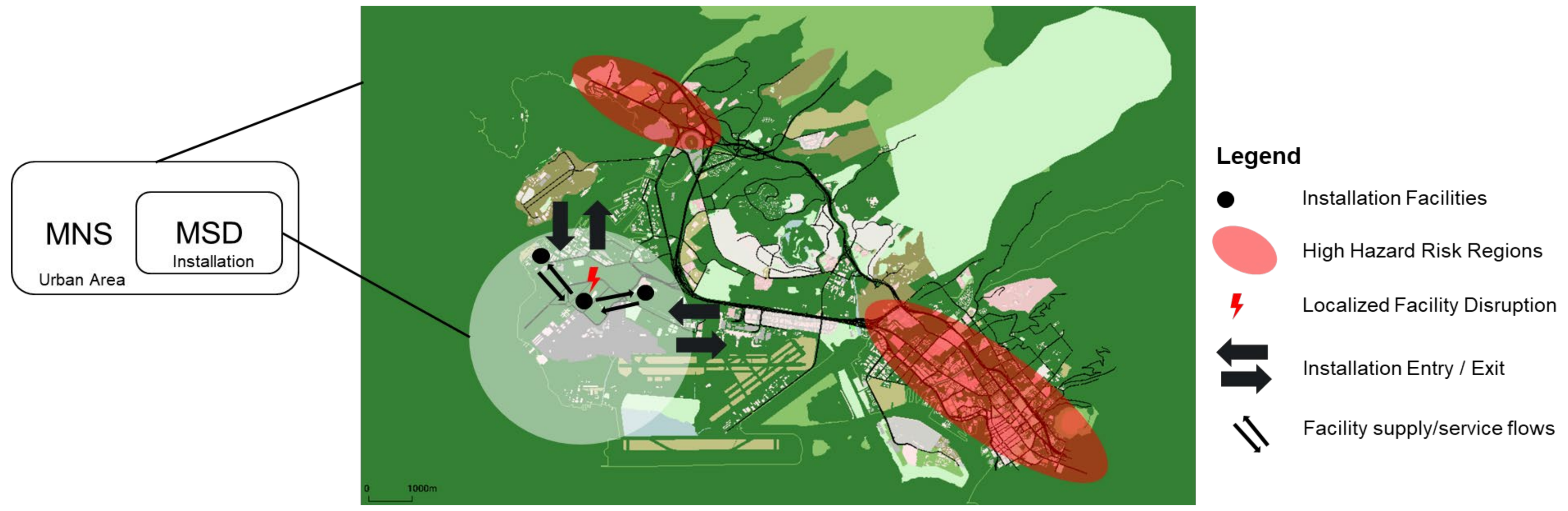
Installation Functions

- Military installations have some similar characteristics of cities or urban areas
- Operational decisions and mission focus is key for ensuring resilience against compound threats



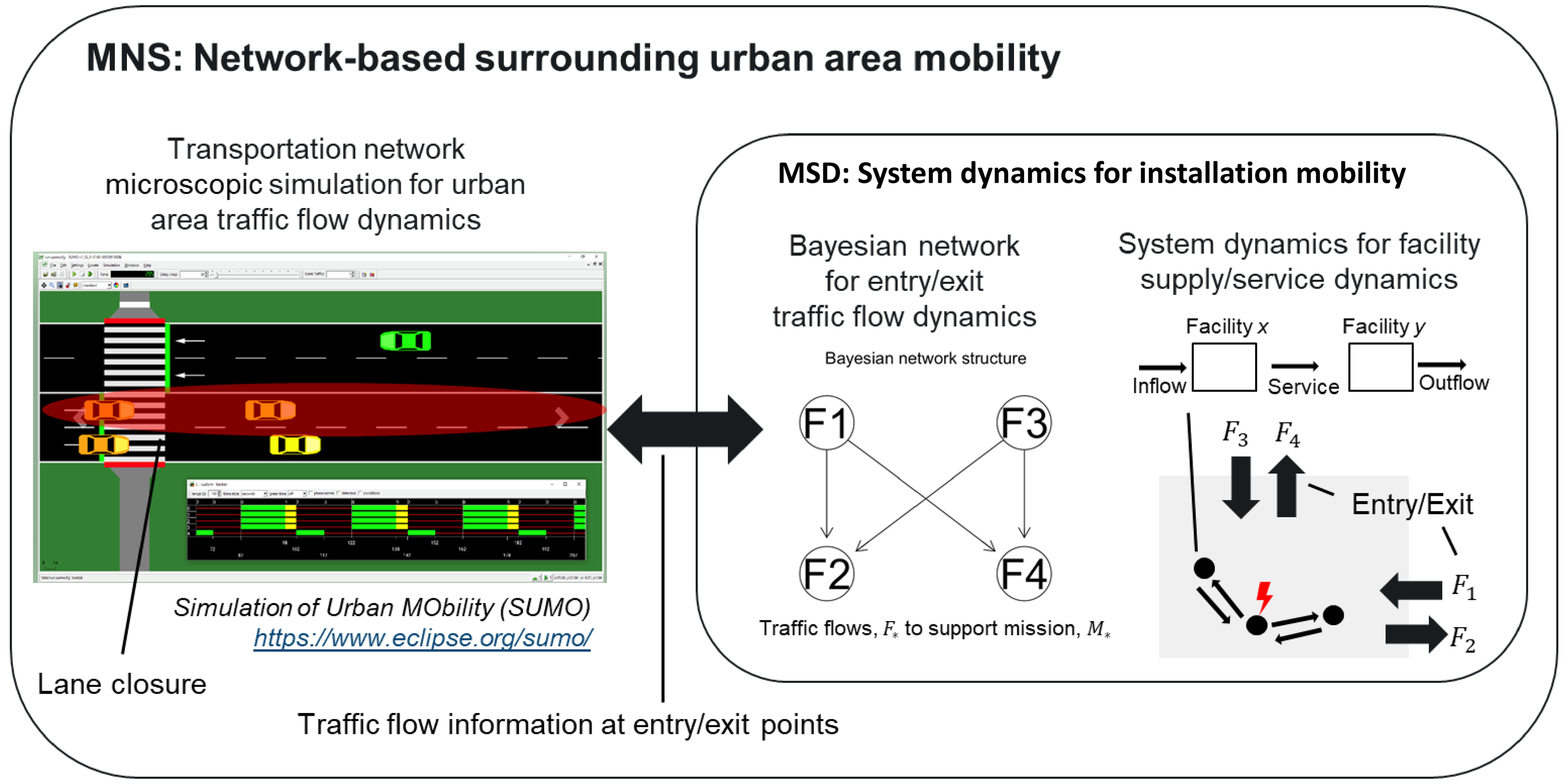
Installation Modeling: Mobility Within and Around an Installation

- Mobility function supports multiple installation missions
- Use urban area road network for installation mobility simulation with trucks and passenger cars
- Incorporate wide area hazard effects in conjunction with localized facility disruption
- Assess mobility impacts via network and entry/exit delays, and facility supply/service disruptions



Modeling and Simulation

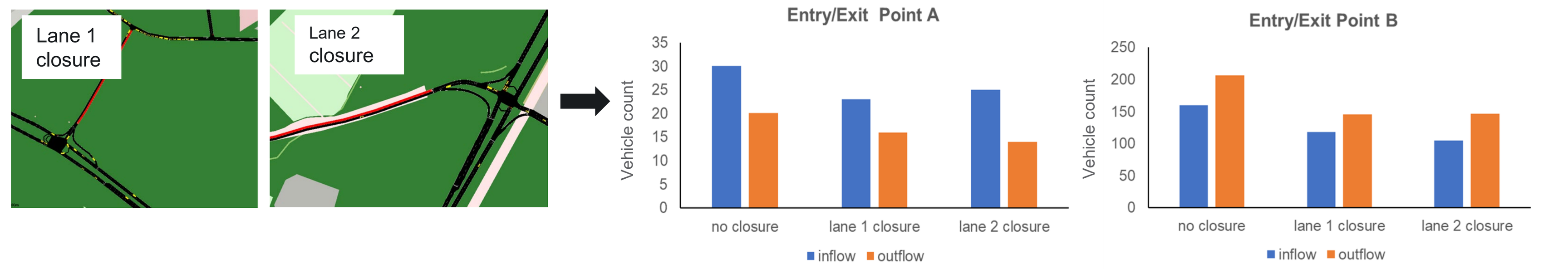
- We represent and implement installation resilience framing and modeling through multiplex networks (Multiplex Network Science (MNS)) complemented by system dynamics (Multiplex System Dynamics (MSD))
- We Leverage network- and system-based approaches depending on data/information availability



Google Maps https://maps.google.com/
SUMO https://www.eclipse.org/sumo/
OpenStreetMap https://www.openstreetmap.org/
https://www.r-project.org/
python https://www.python.org/

Initial Results

- **Initial disruption scenario**: Lane closures in the urban area road network
- **MNS**: Inflow and outflow simulated based on sampling of trips from uniform distributions in SUMO



- **MSD**: Trained and tested a Bayesian network (BN) model with synthetic flow data
- Used Maximum Likelihood Estimation (MLE) for BN model parameter learning

BN Training

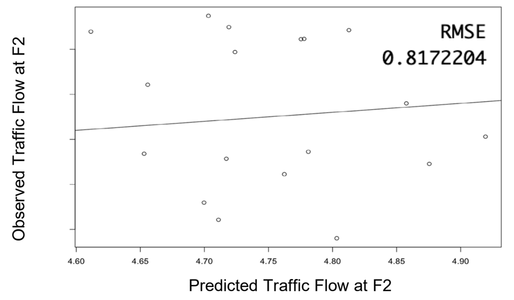
```
Parameters of node F2 (Gaussian distribution)

Conditional density: F2 | F1 + F3
Coefficients:
(Intercept)          F1            F3
 4.81550897   0.03232503  -0.14779816
Standard deviation of the residuals: 0.9773178
```

```
Parameters of node F4 (Gaussian distribution)

Conditional density: F4 | F1 + F3
Coefficients:
 (Intercept)           F1              F3
5.7563802456  0.0009152342  0.3396541782
Standard deviation of the residuals: 1.544982
```

BN Testing



Next Steps

- Further define compound installation disruption scenarios of interest
- Develop installation resilience curves with failure and recovery dynamics
- Generate decision-support insights based on installation resilience curves

Key Publication

Chikkagoudar, Chatterjee, Bharadwaj, Ganguly, Kompella, Thorsen, "Assurance by Design for Cyber-physical Data-driven Systems," in IoT for Defense and National Security, IEEE, 2023