# Modeling Complex Sociotechnical Systems: Systemic Risk and Emergence

Abhishek Sivaram, Vipul Mann, Laya Das, and Venkat Venkatasubramanian*

CRIS Lab, Department of Chemical Engineering, Columbia University

COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science
COMPLEX RESILIENT INTELLIGENT SYSTEMS

## Complex Sociotechnical Systems and Emergence

Figure 1: SARS (2003), BP Deepwater Horizon Oil Spill (2010), Subprime Crisis (2008), and Northeast Blackout (2003)

- Complex adaptive systems engineering
  - Need to go beyond analyzing them as independent one-off accidents
  - Common underlying patterns behind systemic failures
  - Need a unifying complex systems engineering perspective of sociotechnical systems
  - Need to recognize emergent phenomena and understand the underlying mechanisms
- Failures (lessons) at all levels
  - Individual
  - Corporation
  - Corporate board
  - Government: policies and regulations
  - Community
  - National
- Teleo-Centric System Model for Analyzing Risks and Threats (TeCSMART) (Venkatasubramanian and Zhang, 2016)

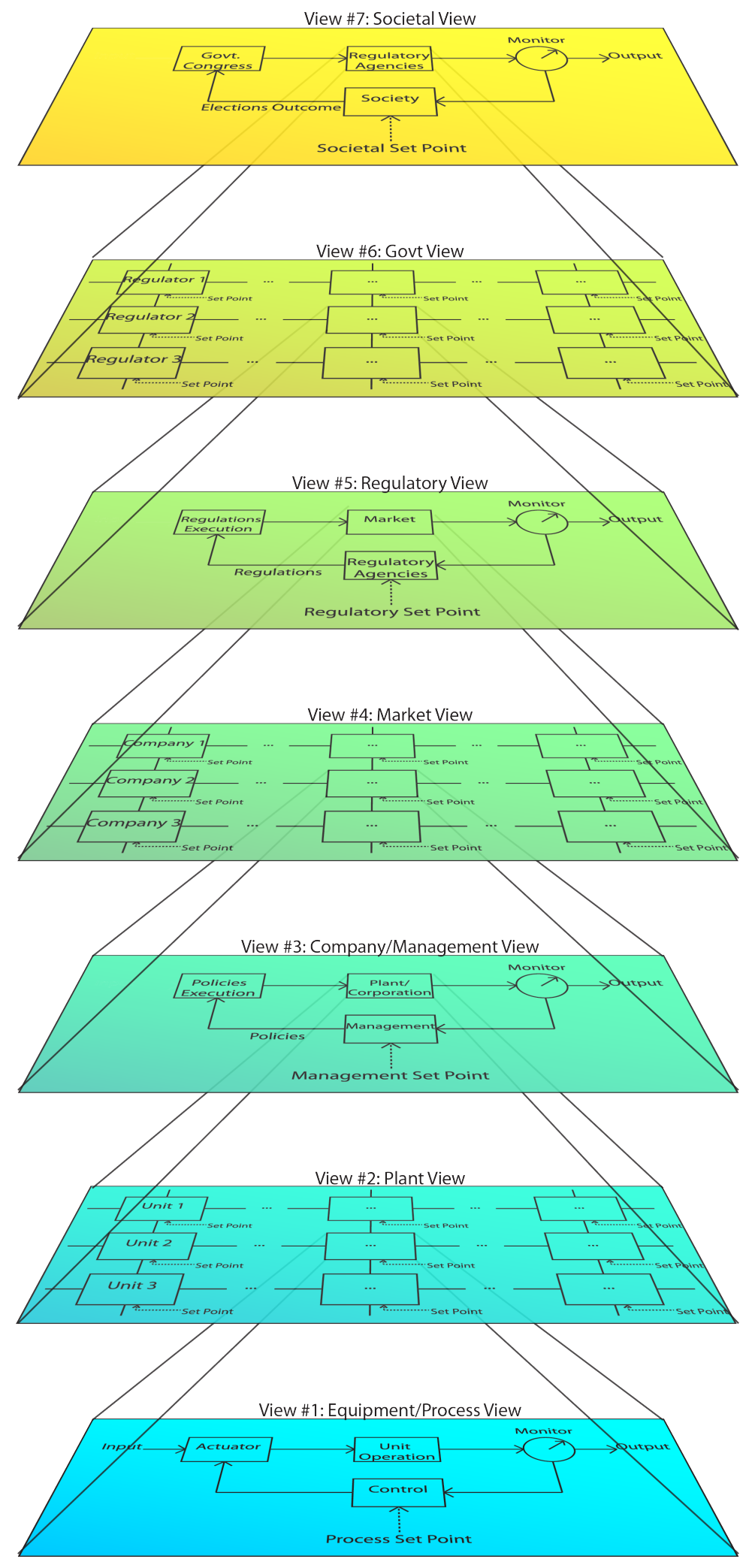
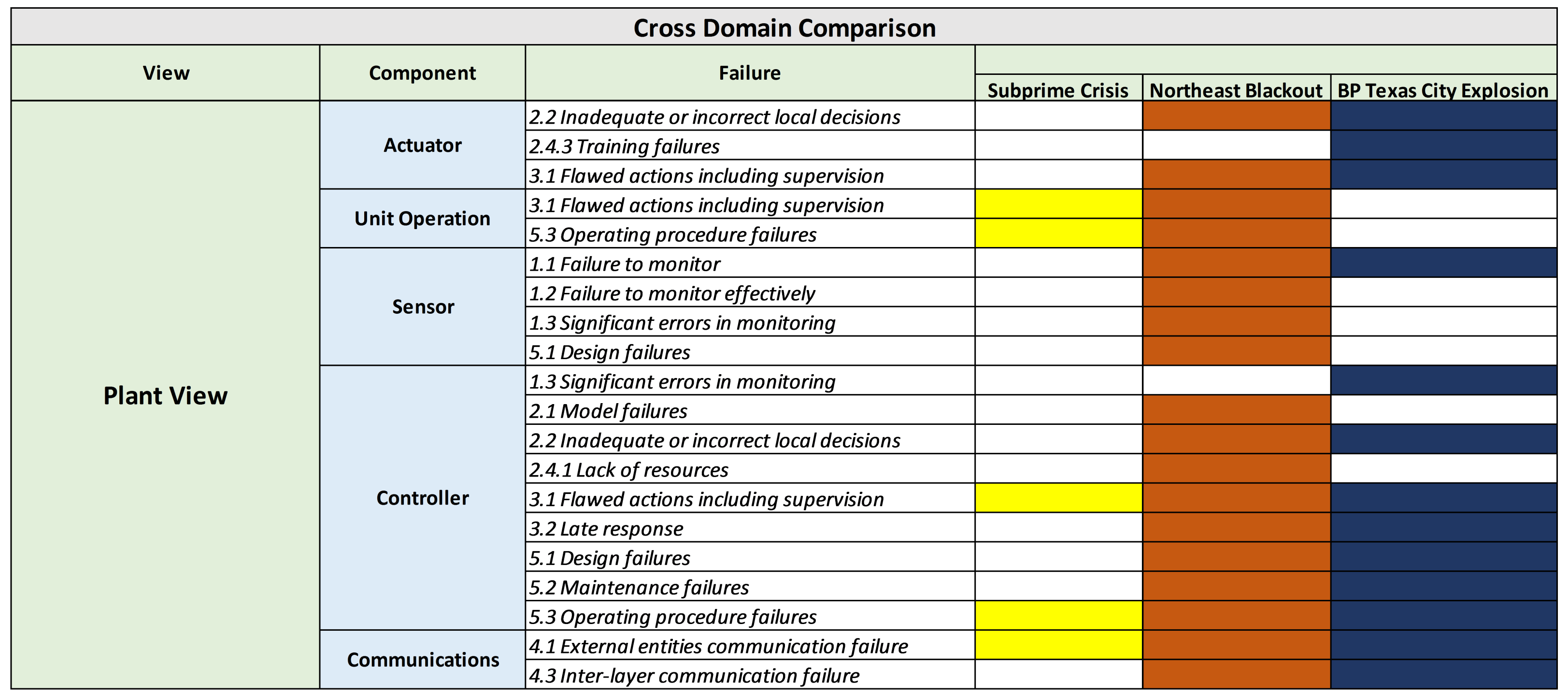


Figure 2: TeCSMART



| Cross Domain Comparison | | | | | |
|---|---|---|---|---|---|
| View | Component | Failure | | | |
| | | | Subprime Crisis | Northeast Blackout | BP Texas City Explosion |
| Plant View | Actuator | *2.2 Inadequate or incorrect local decisions* | | 🟧 | 🟦 |
| | | *2.4.3 Training failures* | | | 🟦 |
| | | *3.1 Flawed actions including supervision* | | 🟧 | 🟦 |
| | Unit Operation | *3.1 Flawed actions including supervision* | 🟨 | 🟧 | |
| | | *5.3 Operating procedure failures* | 🟨 | 🟧 | |
| | Sensor | *1.1 Failure to monitor* | | 🟧 | 🟦 |
| | | *1.2 Failure to monitor effectively* | | 🟧 | |
| | | *1.3 Significant errors in monitoring* | | 🟧 | |
| | | *5.1 Design failures* | | 🟧 | |
| | Controller | *1.3 Significant errors in monitoring* | | | 🟦 |
| | | *2.1 Model failures* | | 🟧 | |
| | | *2.2 Inadequate or incorrect local decisions* | | 🟧 | 🟦 |
| | | *2.4.1 Lack of resources* | | 🟧 | |
| | | *3.1 Flawed actions including supervision* | 🟨 | 🟧 | 🟦 |
| | | *3.2 Late response* | | 🟧 | 🟦 |
| | | *5.1 Design failures* | | 🟧 | 🟦 |
| | | *5.2 Maintenance failures* | | 🟧 | 🟦 |
| | | *5.3 Operating procedure failures* | 🟨 | 🟧 | 🟦 |
| | Communications | *4.1 External entities communication failure* | 🟨 | 🟧 | 🟦 |
| | | *4.3 Inter-layer communication failure* | | 🟧 | 🟦 |

Figure 3: Comparative Analysis

## Causal Modeling of Process Systems

- How do we understand the causal links between different variables in a process?
- Creating causal graphs using entropic correlation in time
  - Data-driven setting for identifying flow of information in a process system
  - Captures higher order correlations between system variables
  - Hierarchical strategy to estimate causal links for the plant-level operations
- **Directed Graph As a Modeling Tool for Analyzing Systemic Risk in Process Systems** (Suresh et al., 2019)

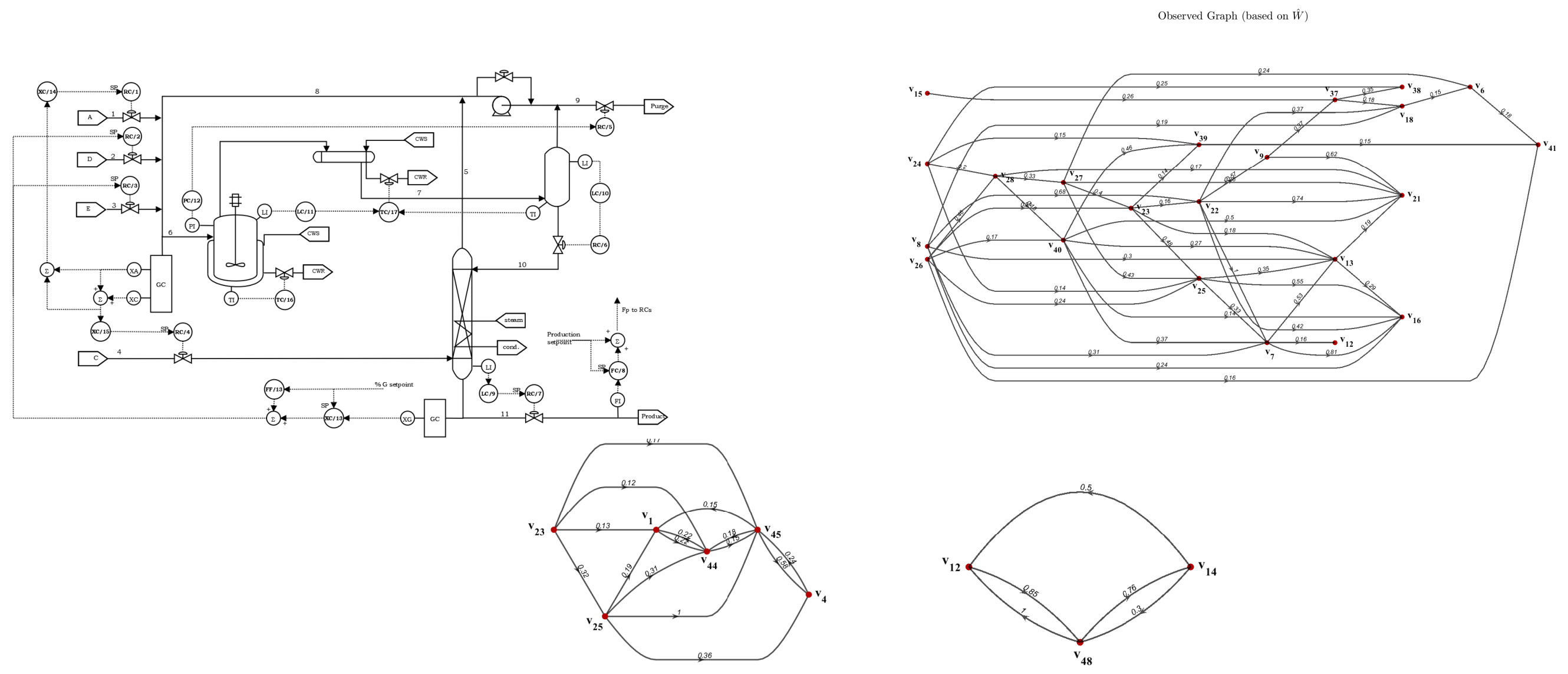


Figure 4: Tennessee Eastman Process, Plant-level causal model, Unit level causal models

## Process Modeling from Data

- What do neural networks learn?
- **Hidden representations of deep neural network towards function approximation and classification**
- Deep nets, a *few complex patterns*
- Wide nets, a *lot of simple patterns*
- Black box models like neural networks fail to explain the reason for their recommendation
- Model Hypothesis Generation using Genetic Algorithm
- **Mechanism identification using Genetic Feature Extraction and Statistical Testing (GFEST)**

Figure 5: Data, Deep Network Representation, Wide Network Representation

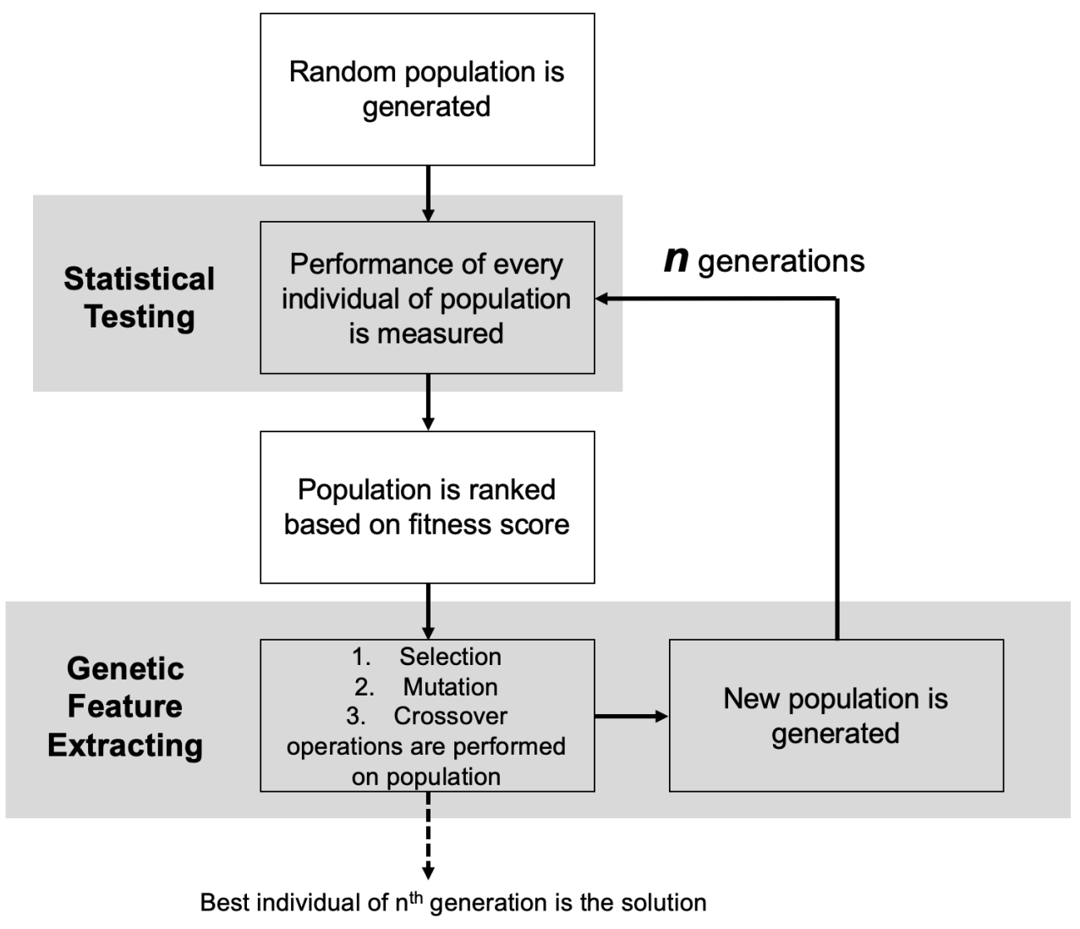


Figure 6: GFEST algorithm

## References

Yu Luo, Garud Iyengar, and Venkat Venkatasubramanian. Social influence makes self-interested crowds smarter: An optimal control perspective. *IEEE Transactions on Computational Social Systems*, 2018.

Resmi Suresh, Abhishek Sivaram, and Venkat Venkatasubramanian. A hierarchical approach for causal modeling of process systems. *Computers & Chemical Engineering*, 123:170–183, 2019.

Venkat Venkatasubramanian and Zhizun Zhang. Tecsmart: A hierarchical framework for modeling and analyzing systemic risk in sociotechnical systems. *AIChE Journal*, 2016.

## Multi-Agent Control with Soft Feedback

- How to coordinate multiple intelligent agents such that the crowd is collectively wiser?
- Regulator's dilemma: balancing between over- and under-regulation
  - Over-regulation hinders innovation, progress, and economic growth
  - Under-regulation results in safety threats and risk

The *i*-th agent can accept, reject, or partially accept the soft feedback $u$:

$$z_i^+ = (1-\beta_i)\Big(g_i(z_i)+\omega_i\Big)+\beta_i u, \quad \beta_i \in [0,1], \quad \omega_i \sim \mathcal{N}(0,\sigma_\omega), \quad u = \sum_i \frac{z_i}{n}$$

- **Social Influence Makes Self-Interested Crowds Smarter: An Optimal Control Perspective** (Luo et al., 2018)

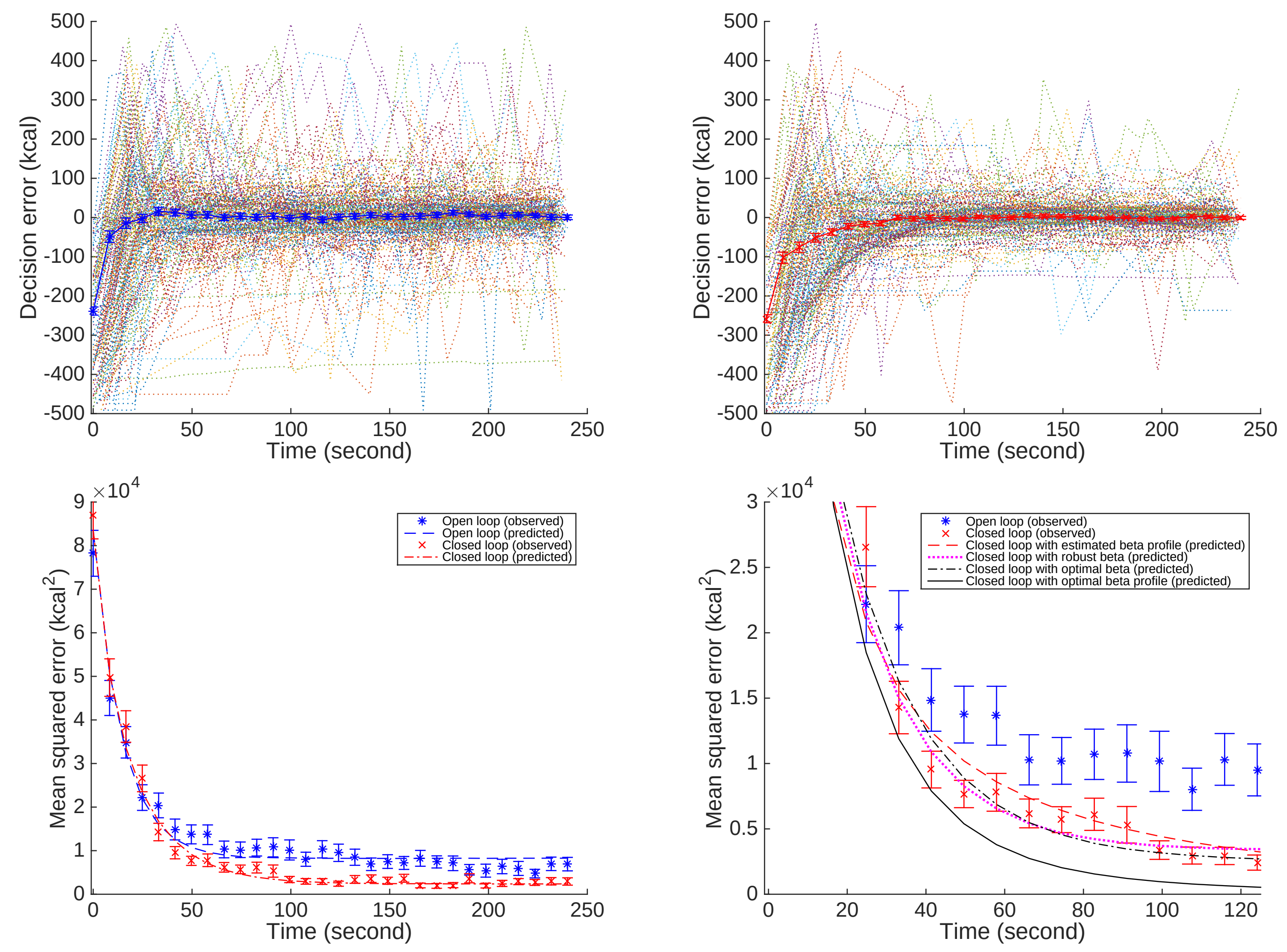


Figure 7: Experiment, System Identification, and Optimal Control Results

## Agent Performance on a Network Topology

- Optimal communication architectures
- Particle Swarm Optimization as test bed
  - *High information transfer* hinders exploration
  - *Low information transfer* hinders efficiency
  - *Robust* topologies are generally not *efficient*
- Design guidelines to ensure efficient and robust networks

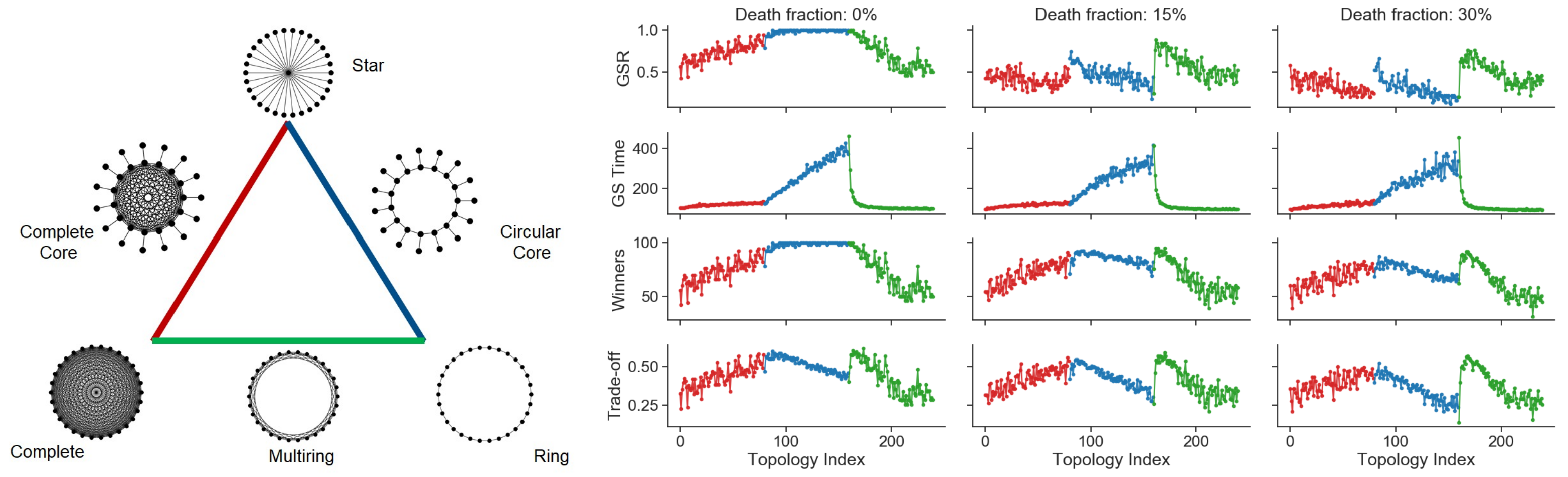


Figure 8: Design Spectrum, Performance Results

cris.cheme.columbia.edu

Mar, 2020

venkat@columbia.edu