Resilience Modeling For Post-Disaster Recovery of Interdependent Systems: Application To Inland Port Disasters

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Defining Economic Resilience

... an ability exhibited by a system that allows it to recover from a disruptive event in a desired time and with an acceptable cost, noting that resilience is planned for in advance of a disruptive event through preparedness investments and activities...

Research Questions

- How to quantify and build metrics for economic resilience?
- How to use economic resilience planning for decision-making guidelines?

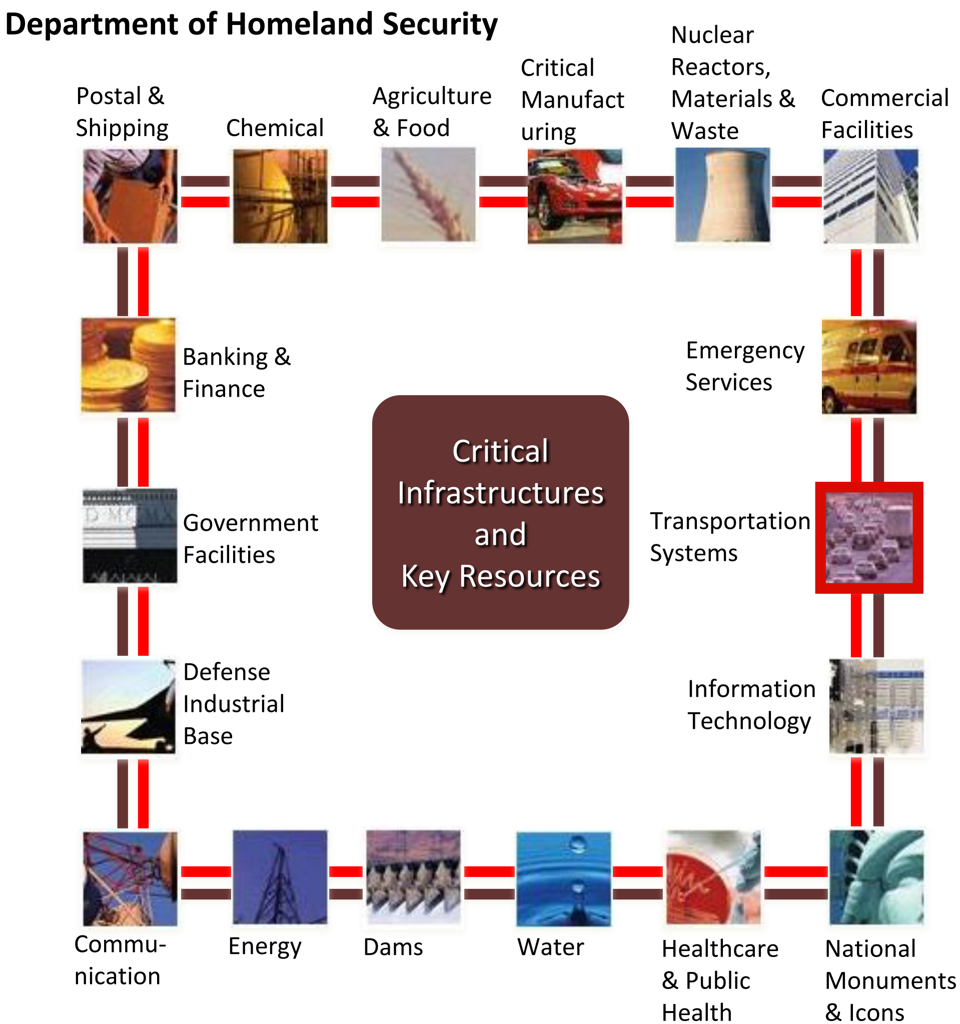
The Motivation

The Methodology

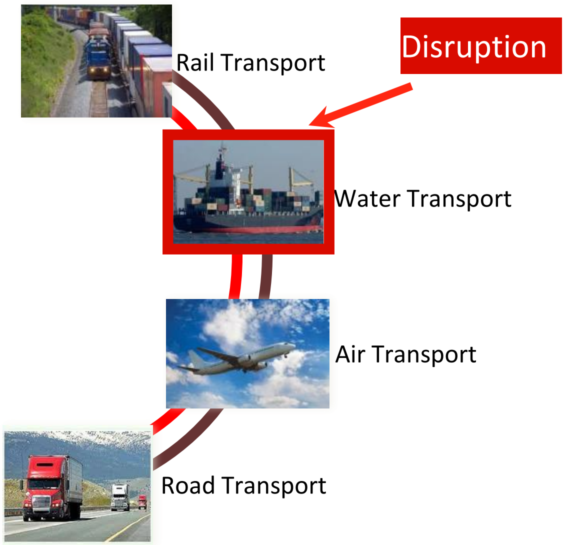
The Application

The Conclusions

Interdependent Infrastructures



Resilience is particularly important in interdependent systems



Disruptions can propagate, resulting in direct as well as wider-spread indirect impacts.

Motivation and Application

Motivation: interdependent systems

Stand alone sector		Interdependent economy
Easier quantification, easier planning for resilience, focus on self interests	⟷ Consider both	Increased behavioral complexity, spatial considerations

Incorporation of interdependence in sector planning to provide holistic picture of economic recovery planning from disaster

Application: multi-modal transport

Inland waterway port disruptions		Industries using port
Security concerns, multiple operations	⟷ Impact	Widespread impacts (multi-industry, multi-regional)

As US traffic congestion increases, growth of inland waterways will only increase (e.g., containerized freight)

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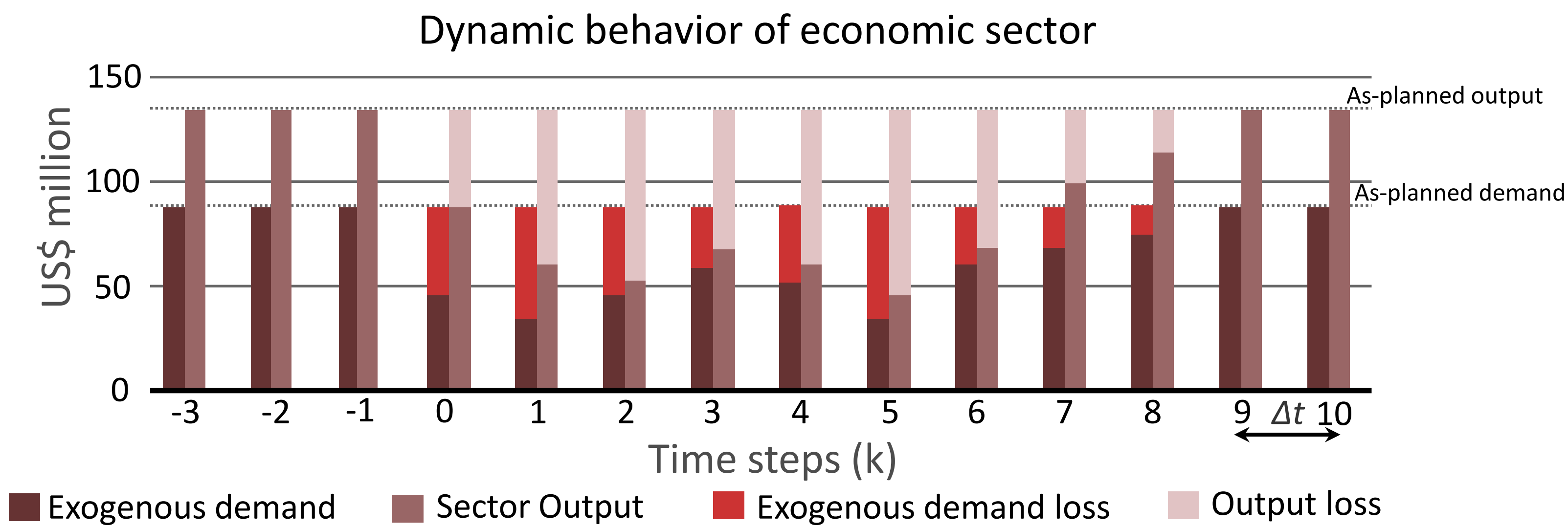
Measuring Disruption Impacts



Consequences of disruption can be expressed in terms of the output and demand loss normalized by the as-planned sector output

Inoperability(q) = [Output loss] /[As - planned output] $\quad q \in [0,1]$

Demand perturbation(c^*) = [Exogenous demand loss] /[As - planned output] $\quad c^* \in [0, c/x < 1]$

Measuring Dynamic Recovery

Dynamic Inoperability Model, based on the DIIM [Lian and Haimes 2006]

n-sector economy

nxn matrix of economic resilience

*nx*1 vector of demand perturbations

$$\mathbf{q}(k+1) = \mathbf{q}(k) + \Delta t\mathbf{K}^{*}[\mathbf{A}^{*}\mathbf{q}(k)+\mathbf{c}^{*}(k)-\mathbf{q}(k)]$$

$k = 0,1,2,\ldots$

*nx*1 vector of sector inoperabilities

nxn normalized matrix for interdependence

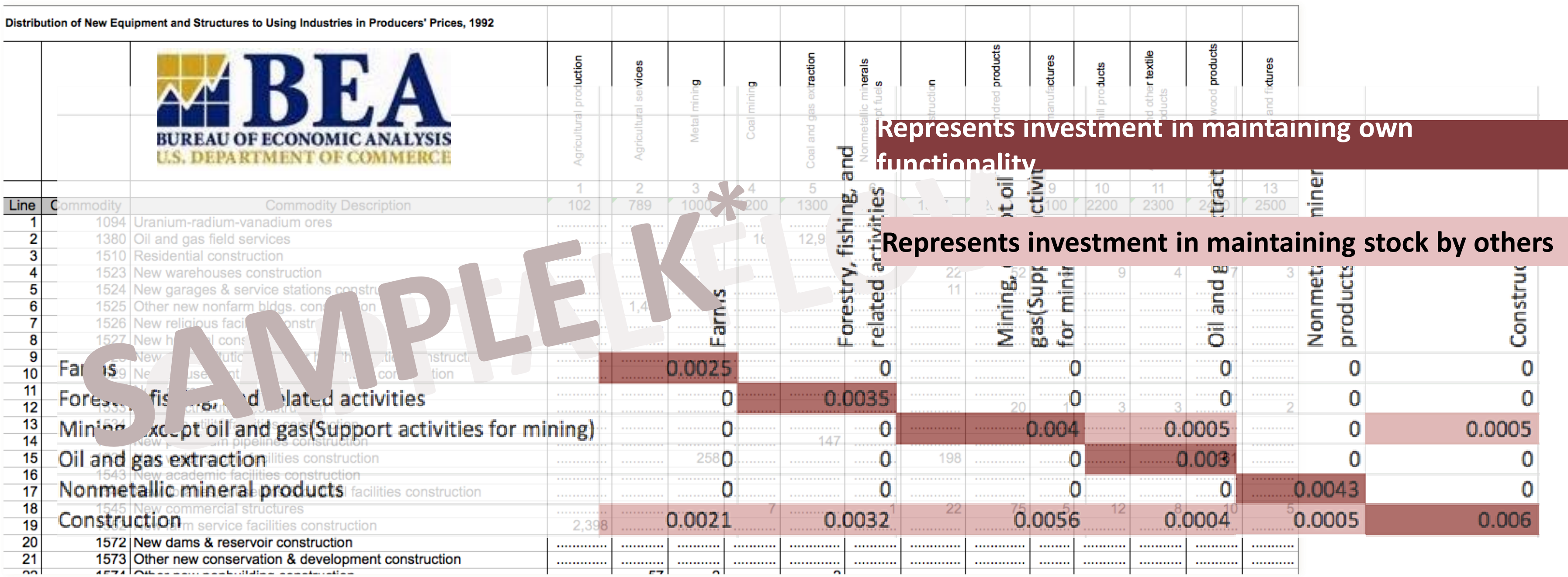
$\mathbf{K}^{*}$ influences the rate at which this term goes to 0, which means there is a balance in demand and supply

Model evolution depends upon $\mathbf{q}(0)$, $\mathbf{K}^{*}$, $\mathbf{A}^{*}$, $\mathbf{c}^{*}(k)$

C. Lian and Y.Y. Haimes. Managing the risk of terrorism to interdependent infrastructure systems through the dynamic inoperability input–output model. *Systems engineering*, 9(3):241–258, 2006.

Structure of K^*

K^* represents a sectors willingness to decrease inoperability by investment in inventory and hardening measures during disruptions by maintaining stocks

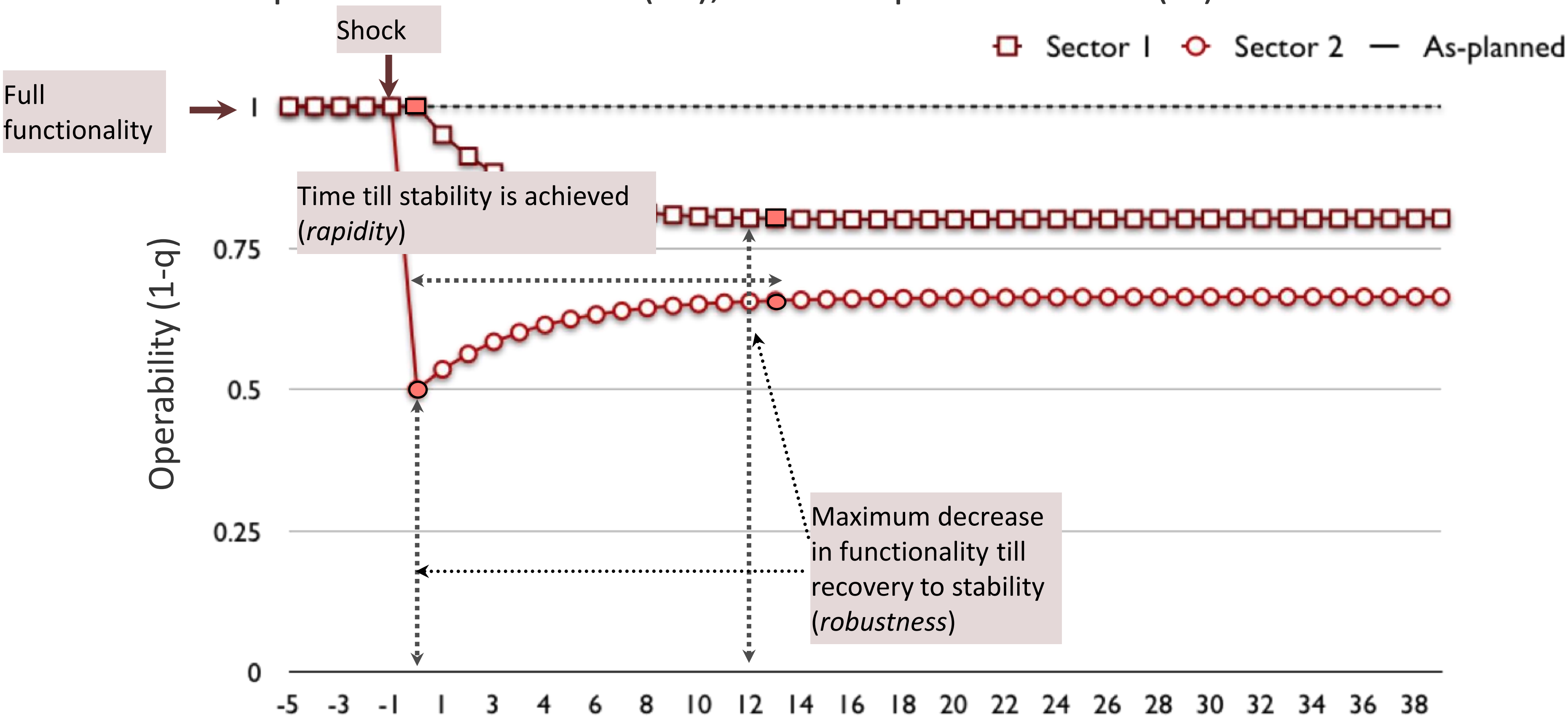


	Farms	Forestry, fishing, and related activities	Mining, except oil and gas(Support activities for mining)	Oil and gas extraction	Nonmetallic mineral products	Construction
Farms	0.0025	0	0	0	0	0
Forestry, fishing, and related activities	0	0.0035	0	0	0	0
Mining, except oil and gas(Support activities for mining)	0	0	0.004	0.0005	0	0.0005
Oil and gas extraction	0	0	0	0.003	0	0
Nonmetallic mineral products	0	0	0	0	0.0043	0
Construction	0.0021	0.0032	0.0056	0.0004	0.0005	0.006

K^* is a sparse matrix with structure similar to the BEA capital flow matrix

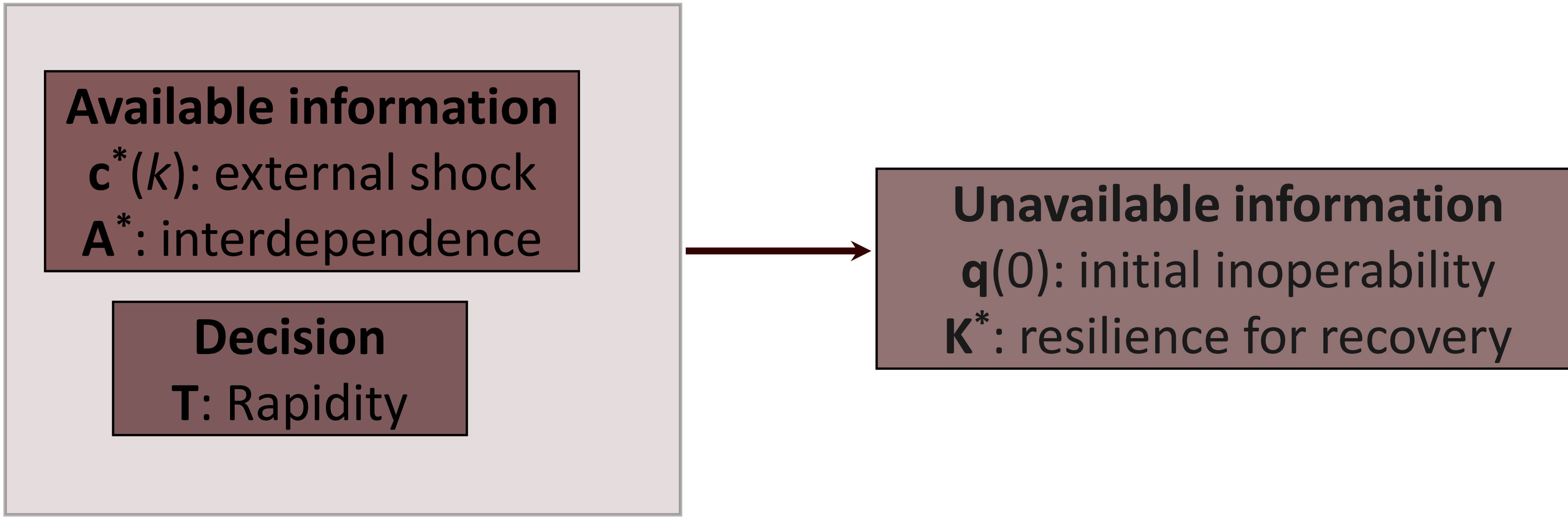
Modeling Dynamic Sector Recovery

Given: interdependence structure (**A***), demand perturbations (**c***)



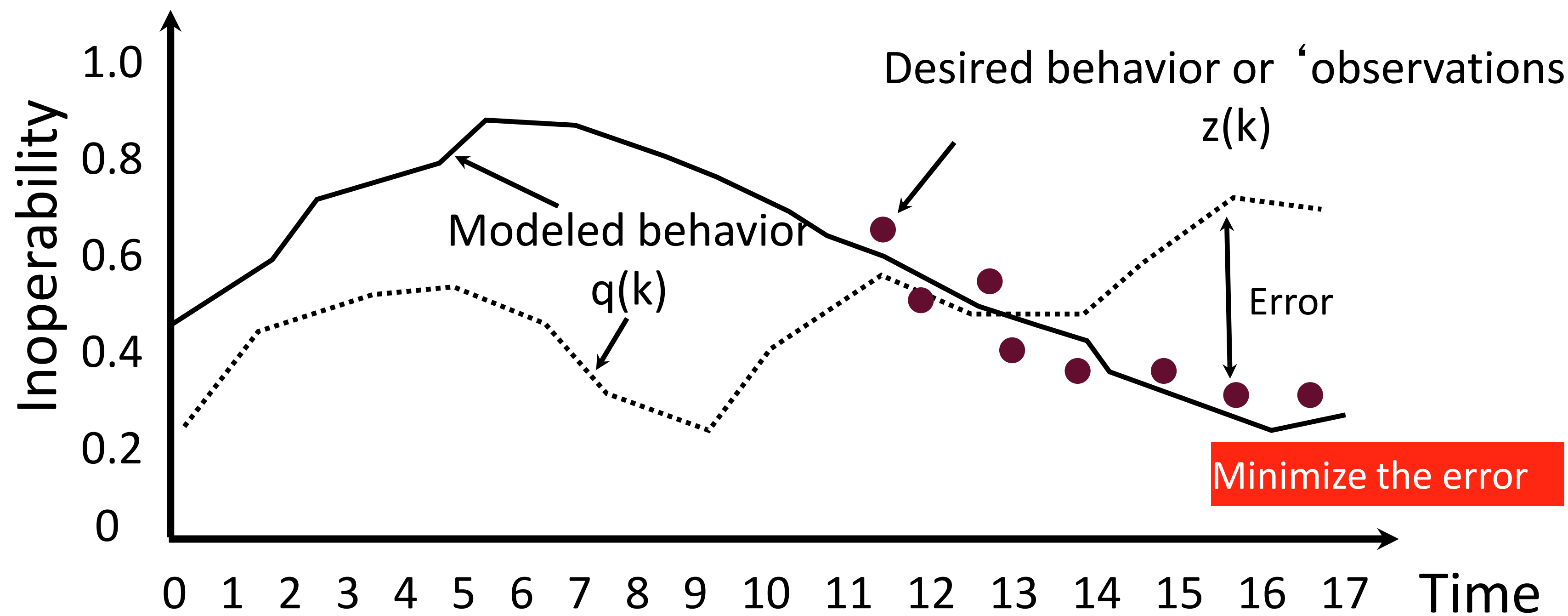
- *Sector robustness* is influenced by the initial inoperability and resilience
- *Rapidity* is influenced by the resilience

Resolving Issues with DIIM



Knowing the time to equilibrium allows us to adjust model parameters so that the equilibrium is reached

Mathematical Formulation



$$\min \sum_{k=T}^{N} [\mathbf{z}(k)-\mathbf{q}(k)]^{T}[\mathbf{z}(k)-\mathbf{q}(k)]$$

subject to

$$\mathbf{q}(k+1) = \mathbf{q}(k) + \Delta t\mathbf{K}^{*}[\mathbf{A}^{*}\mathbf{q}(k)+\mathbf{c}^{*}(k)-\mathbf{q}(k)]$$

Implementing the Algorithm

External inputs

Exogenous demands: $\mathbf{c}^*(k)$
Interdependence: $\mathbf{A}^*$
Time to stability: T

Initial guess

Initial inoperability: $\mathbf{q}(0)$
Resilience coefficients: $\mathbf{K}^*$

Data assimilation

Expected inoperability: $\mathbf{z}(T) = [\mathbf{I} - \mathbf{A}^*]^{-1}\mathbf{c}^*(T)$ + error
Modeled inoperability: $\mathbf{q}(T)$

Minimizing error

min: $\mathbf{e}(T) = \mathbf{z}(T) - \mathbf{q}(T)$

Dynamic feedback for control estimation

Parameter improvement

Update estimates for $\mathbf{q}(0)$ and $\mathbf{K}^*$

Research Contributions

Though the present model is similar in structure to the Dynamic Inoperability Input-Output Model (DIIM) [Lian and Haimes, 2006], it improves on the scope and capability of similar such approaches

Previous studies	Present approach
Interpretation of resilience (K*)	
Is a diagonal matrix	Has off-diagonal elements
Interpretation of initial inoperability (q(0))	
Initial direct impact on sector output	Initial sector response to demand perturbations

C. Lian and Y.Y. Haimes. Managing the risk of terrorism to interdependent infrastructure systems through the dynamic inoperability input–output model. *Systems engineering*, 9(3):241–258, 2006.

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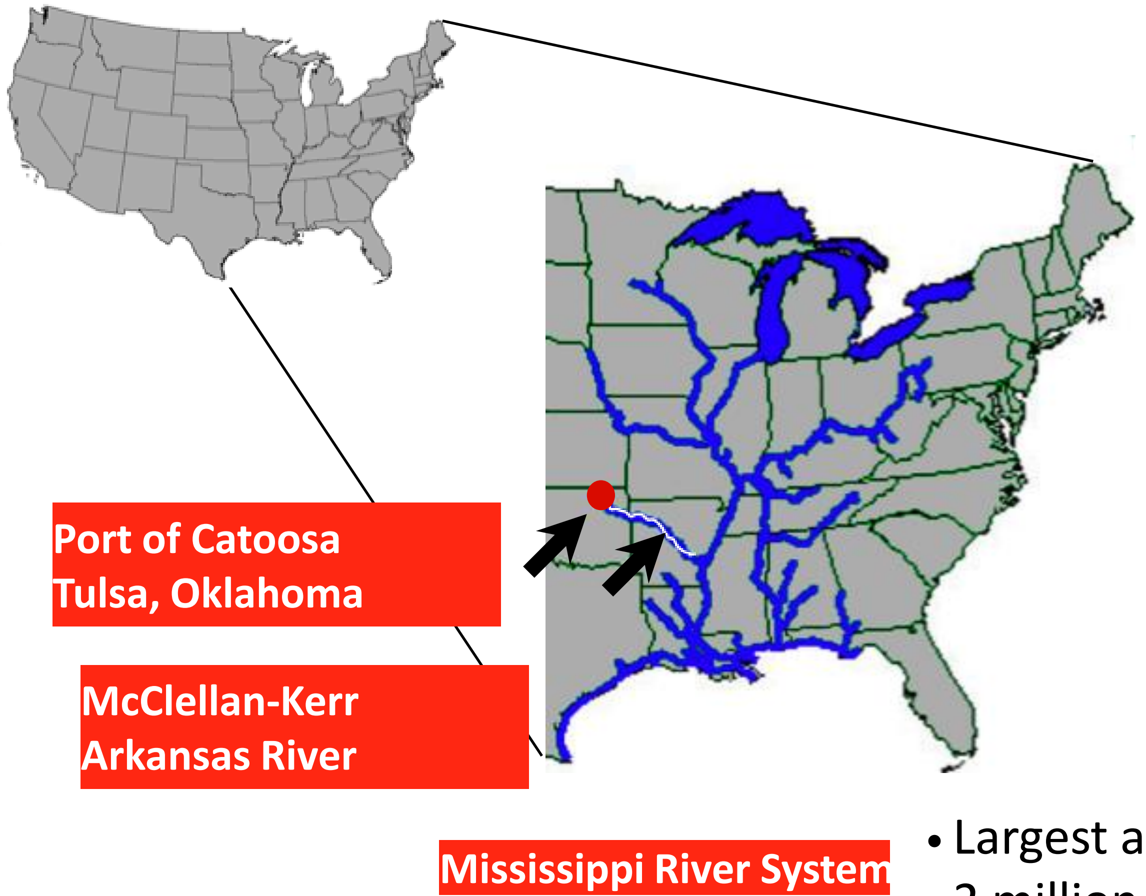
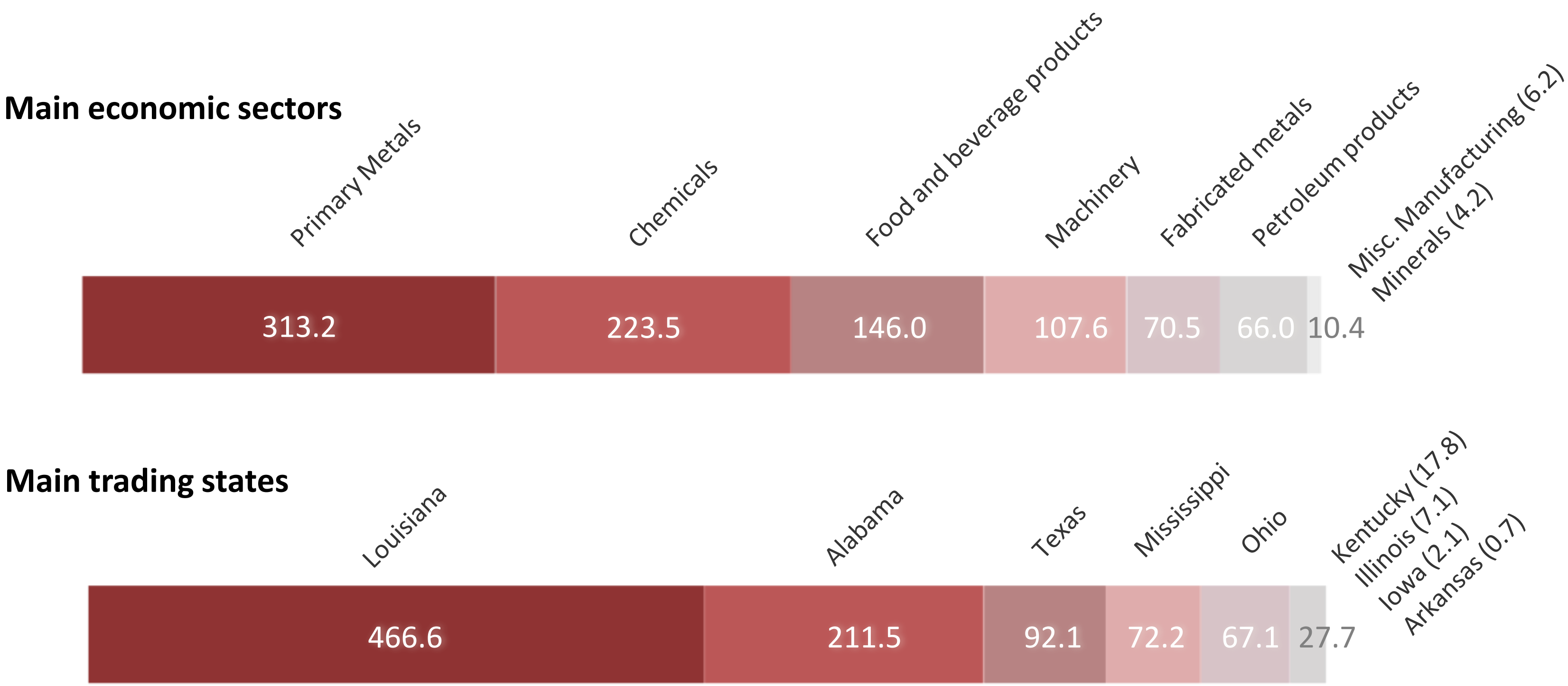
Case Study: Inland Waterway Port



- Largest area-wise inland port in the US
- 2 million tons of cargo annually

Port Waterway Commerce



Total = $937 million

Estimated US$ million annual amount of export-import through Catoosa in 2007*

* Data Sources:
[1] US Army Corps of Engineers, Tulsa Port of Catoosa
[2]US Department of Transportation Research and Innovative Technology Administration

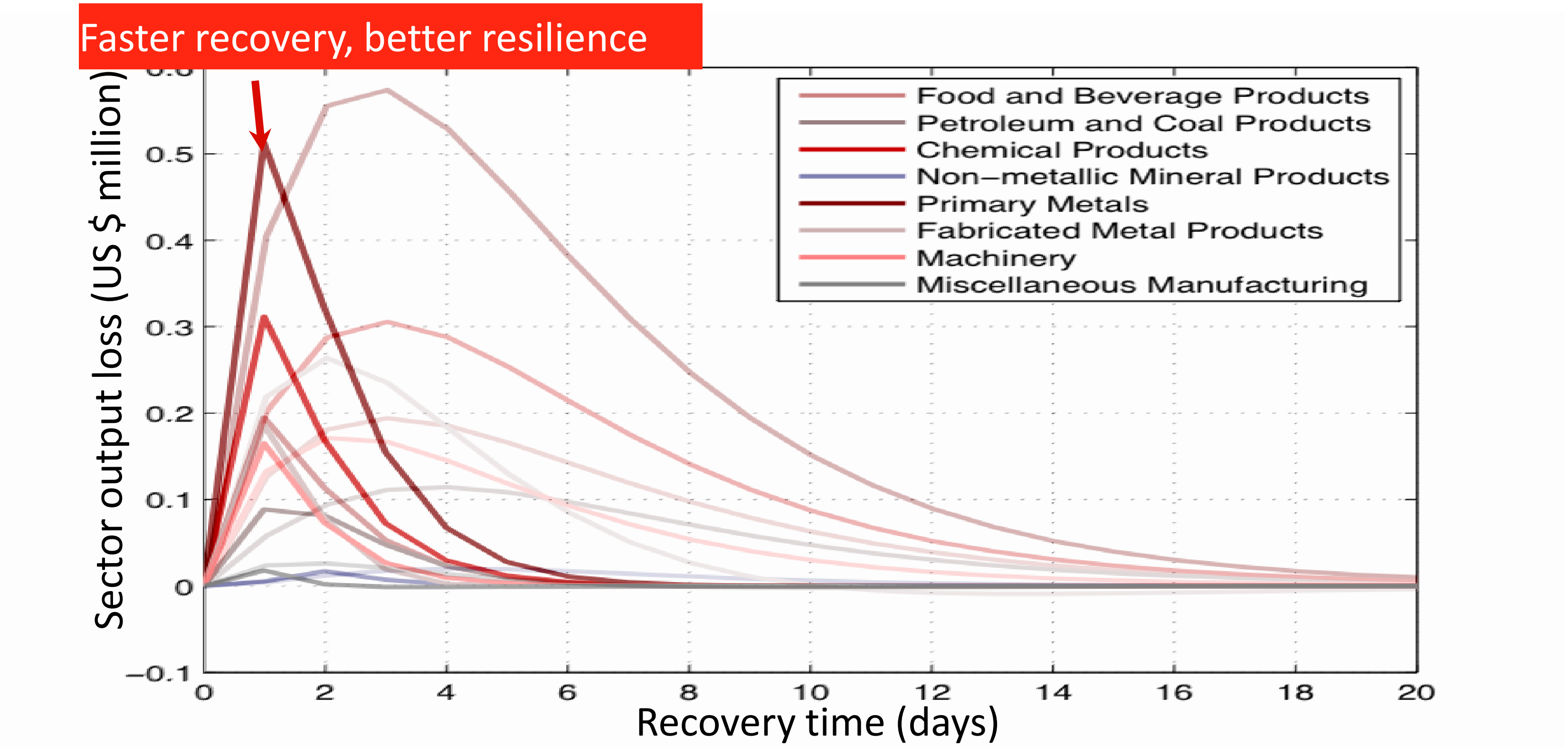
Disruption in Port Commerce

- Closure of the port waterway due to hurricane and floods for 14 days
- Daily loss of export-import is registered as demand losses for industries using the port
- Only source of demand losses for industries across the state
- Maximum daily demand loss of US$ 3.55 million is suffered across port industries

Dynamic Model Behavior

- Rapidity varied from 5 days to 14 days for recovery decisions
- Initial inoperabilities are zero because of localized disruption
- Recovery is complete once stability is achieves

Modeling results for recovery trajectory of port sectors



Planning for Preferred Recovery

Primary Metals

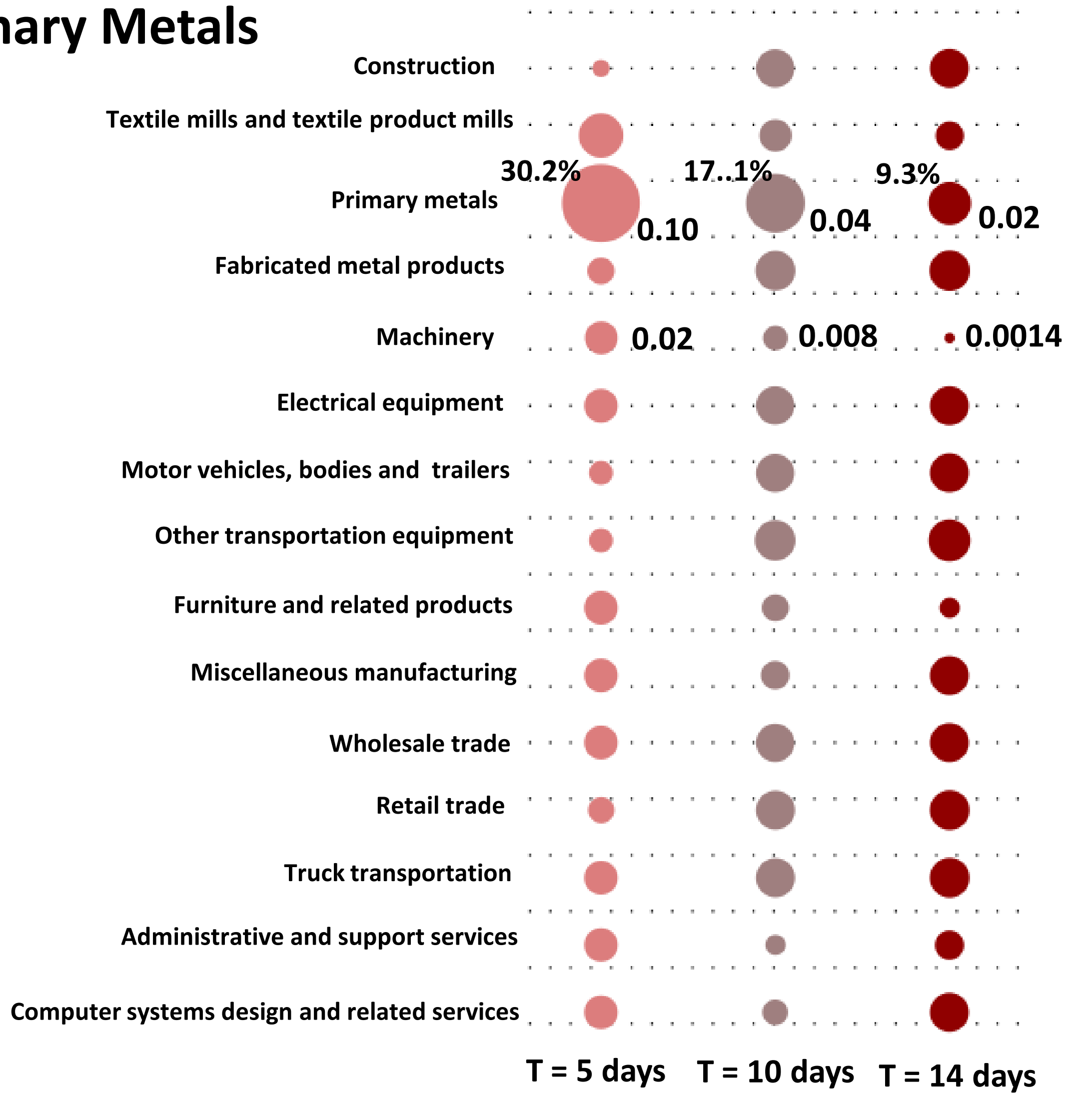
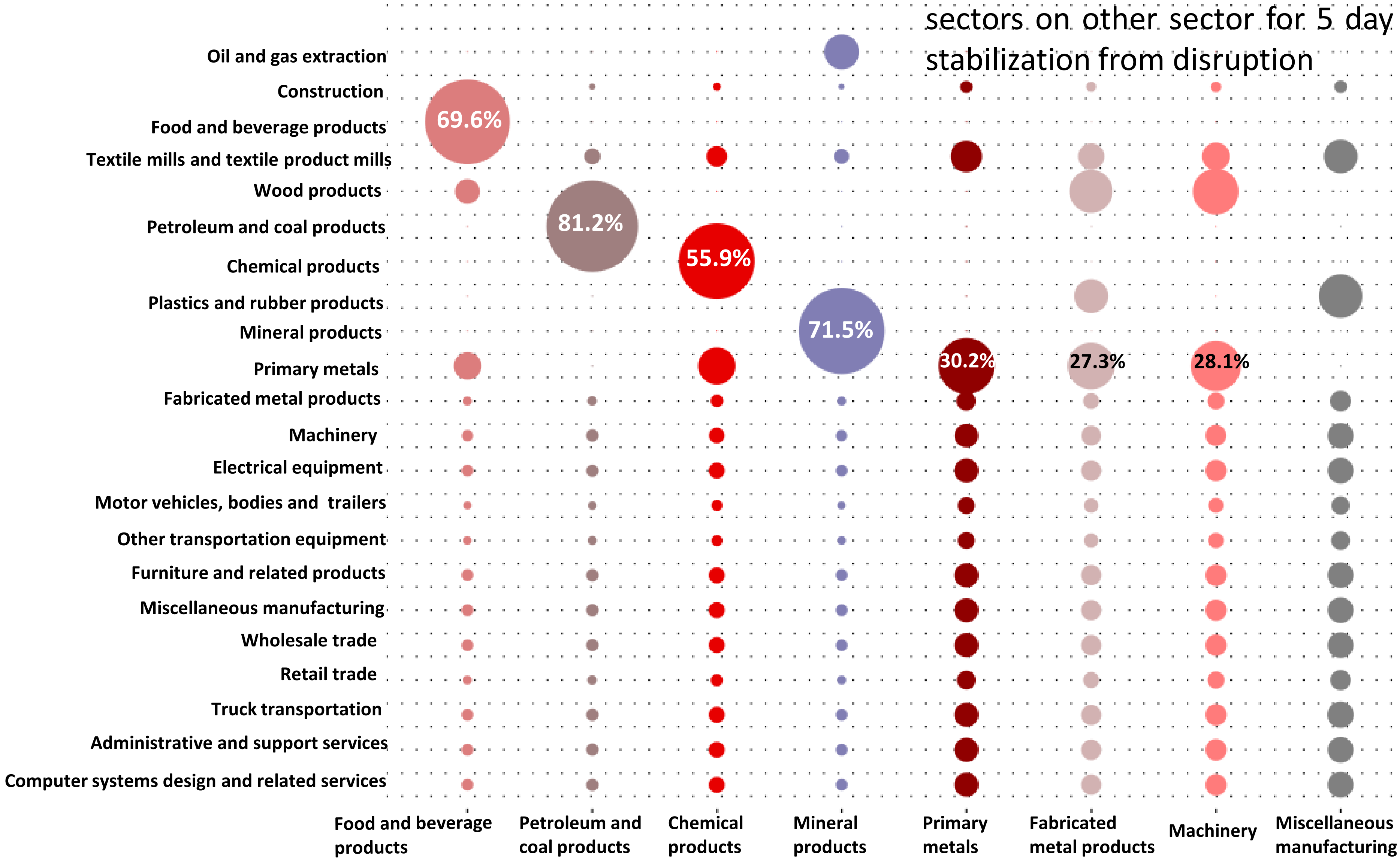


Chart showing degree of investment of Primary Metals into other sectors for recovery

T = Time to stability (rapidity)

Resilience For Port Sectors

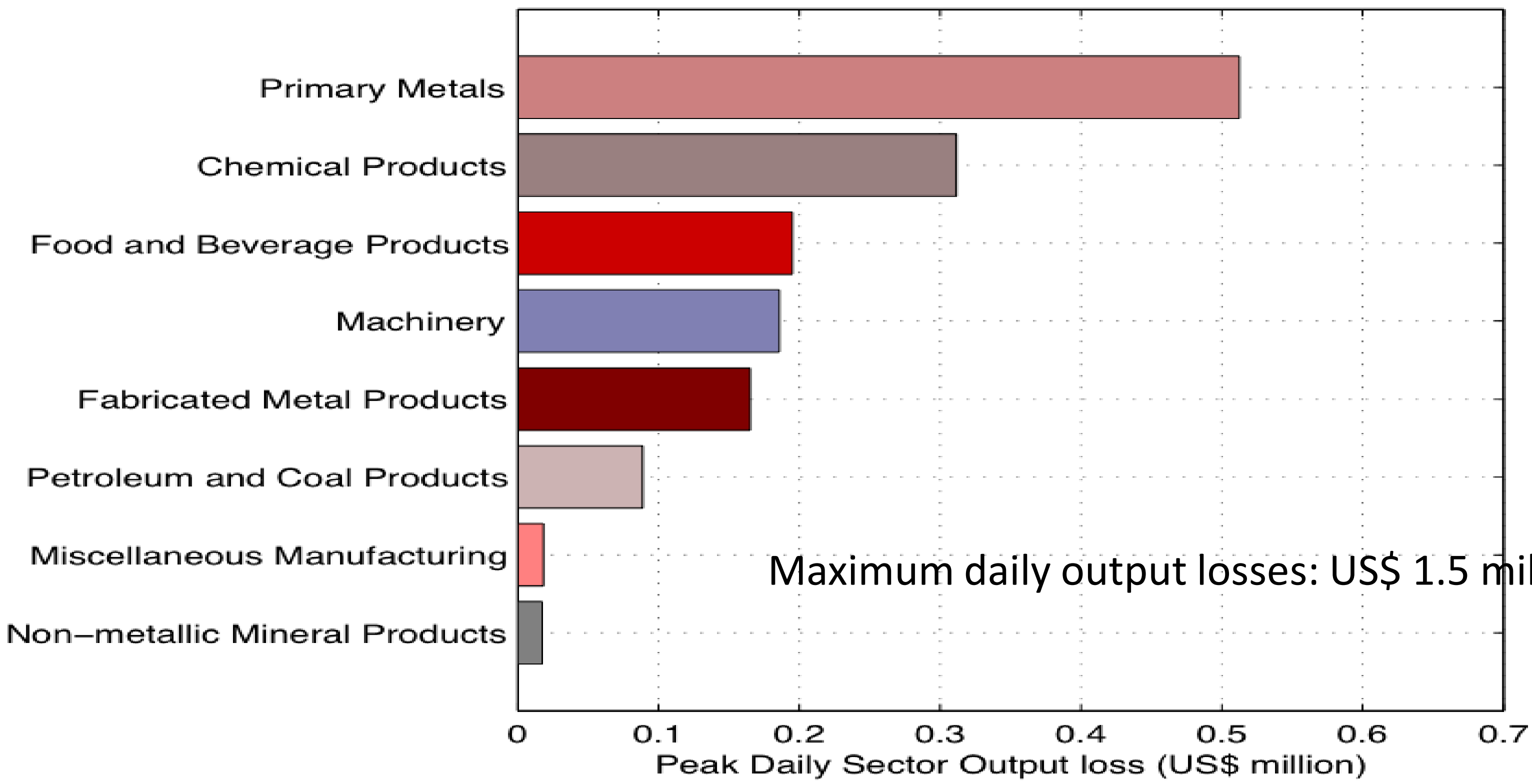
Resilience dependence of port sectors on other sector for 5 day stabilization from disruption



Maximum Loss During Recovery

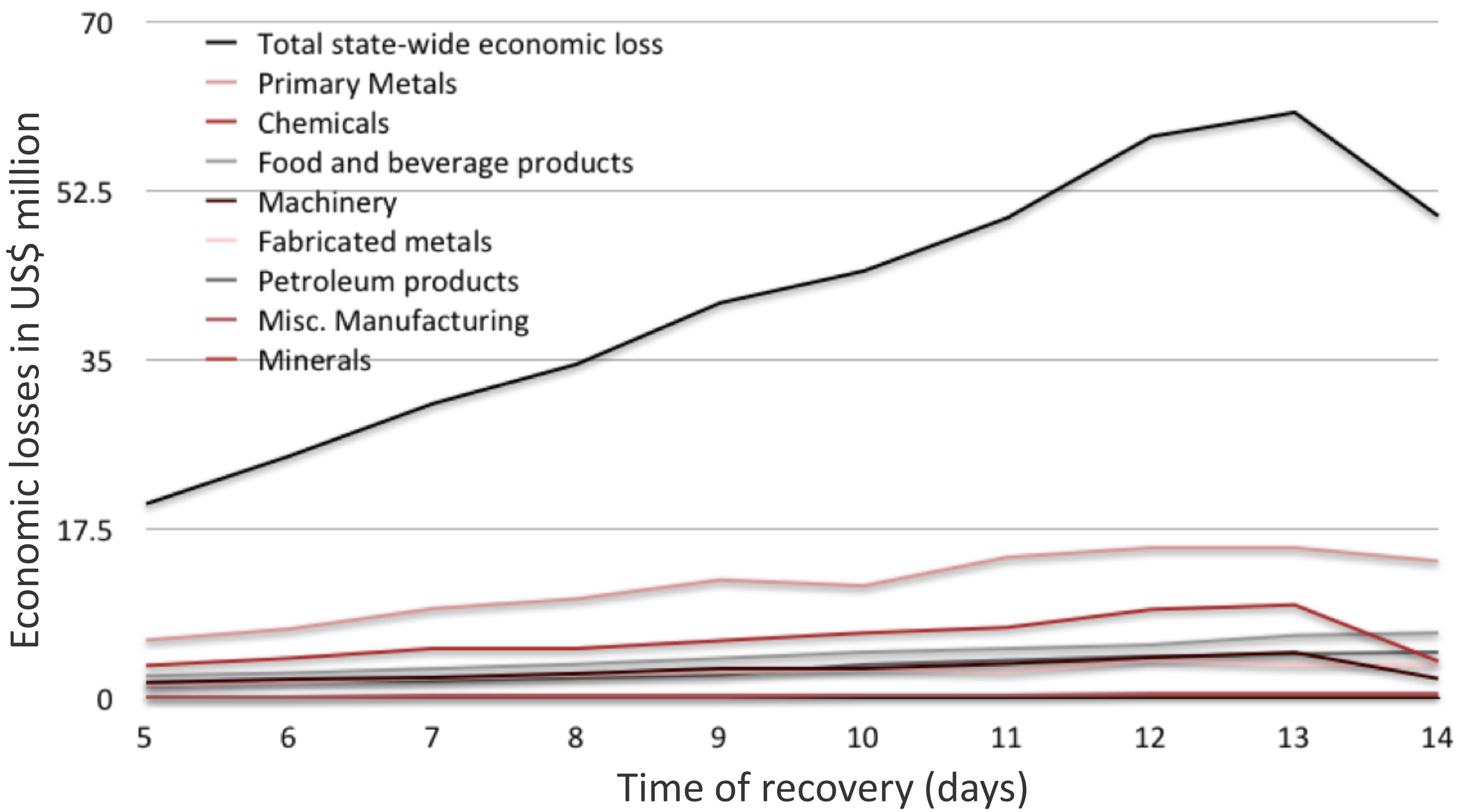
Measure for robustness of economic sectors

Values for sector maximum output losses until recovery in 5 days



Maximum daily output losses: US$ 1.5 million

Total Economic Losses



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Conclusions

Concepts developed

- Development of interdependent resilience structure for sector recoveries
- Decision based on targeting recovery times
- Dynamic data assimilation and feedback control approach handles vastly complex problem

Case study results and thoughts

- The major sector suffering losses at the port is the primary metals sector (0.51 US$ maximum daily loss for 5 day recovery)
- Maximum demand losses of 3.50 US$ million can lead to peak daily output losses of 1.5 US$ million for port industries if they recover in 5 days
- Sate-wide losses can build up to 60 US$ million for a 13 day planned recovery
- Disruptions at Catoosa show sectors should increase their own inventory and structural hardening for faster recovery
- Risk planning behavior shown through estimation of interdependent sector resilience
- Estimates of maximum daily loss before recovery and total economic losses can be combined with resilience estimations to get a decision-making metric

Appreciation

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End of Presentation

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