An Introduction to Inoperability Input-Output Modeling (IIM) as a Tool for Disaster Risk Management

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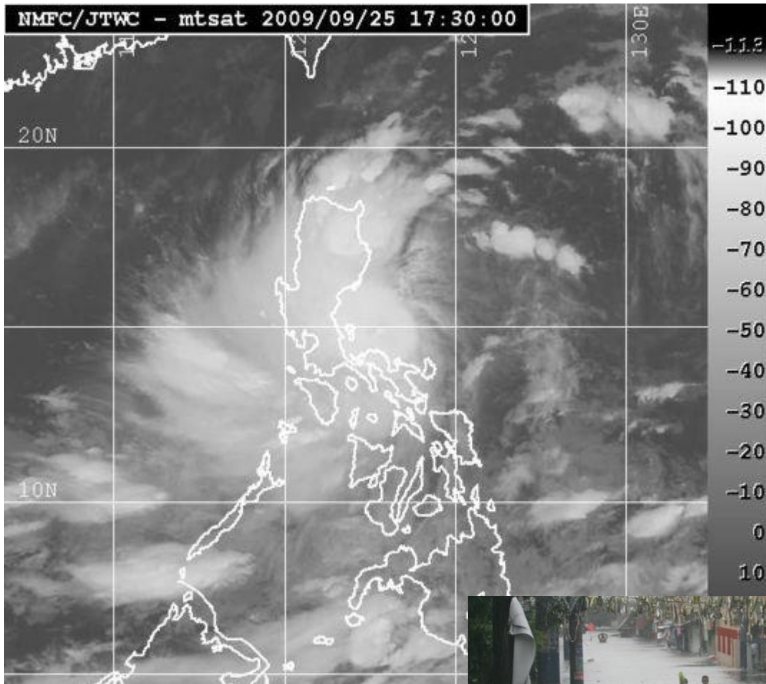
Disaster Vulnerability and Poverty



- The Philippines is one of the most disaster-prone countries in the world
- Research that contributes to **weakening the vicious cycle of disaster vulnerability and poverty** is essential
- The proposed project will develop a **scientific basis for disaster risk management policy** in the country

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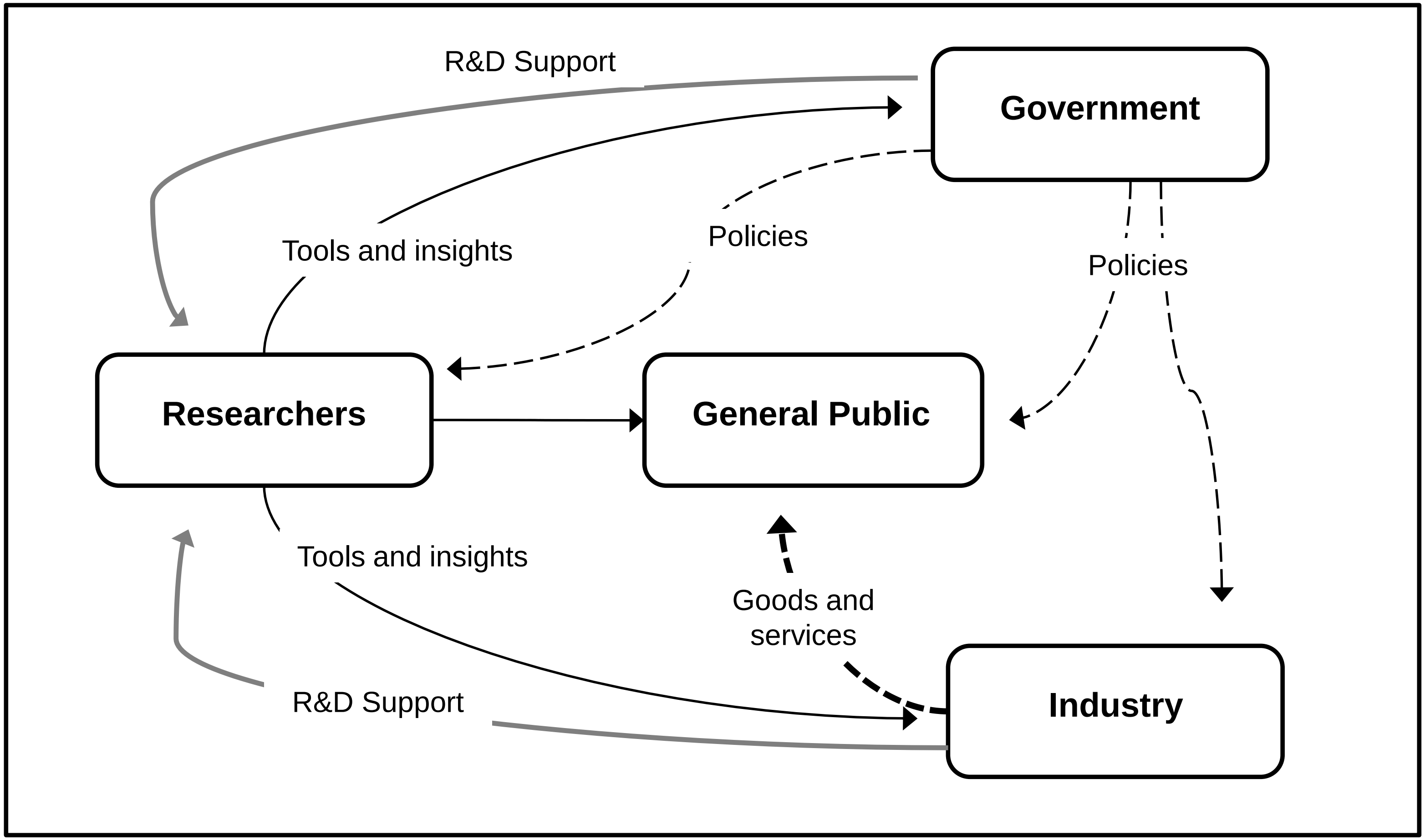
The Role of IIM Research in a Disaster-Prone Country



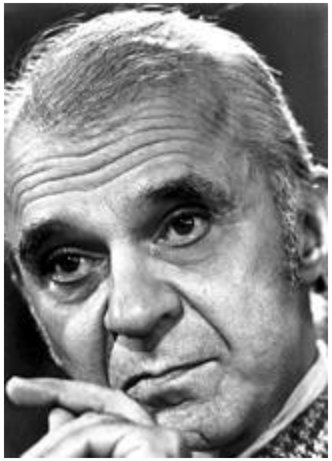
Fast- and Slow-Onset Disasters

Speed of Occurrence	Some Examples
Fast-Onset	➢Typhoons and hurricanes ➢Earthquakes ➢Volcanic eruptions ➢Landslides ➢Tsunamis ➢Disease outbreaks ➢Industrial accidents ➢Terrorist attacks
Slow-Onset	➢Climate change ➢Desertification ➢Biodiversity loss ➢Migration-induced "brain drain" ➢Depletion of non-renewable resources

Example of "Ripple Effects" from Possible Disasters that Threaten the Philippines

Triggering Event	Examples of Collateral Damage
Tsunami hits a major tourist spot	➢Job losses due to hotel closures ➢Small businesses go bankrupt
Massive flu outbreak hits major cities	➢Labor shortage across multiple sectors ➢Loss of industrial output across multiple sectors
Ash from volcanic eruption cripples an international airport	➢Manufacturing plant closures ➢Tourism losses
Prolonged drought due to climate change	➢Crop failure ➢Shutdown of hydroelectric facilities ➢Loss of industrial output ➢Reduced investment ➢Loss of livelihood

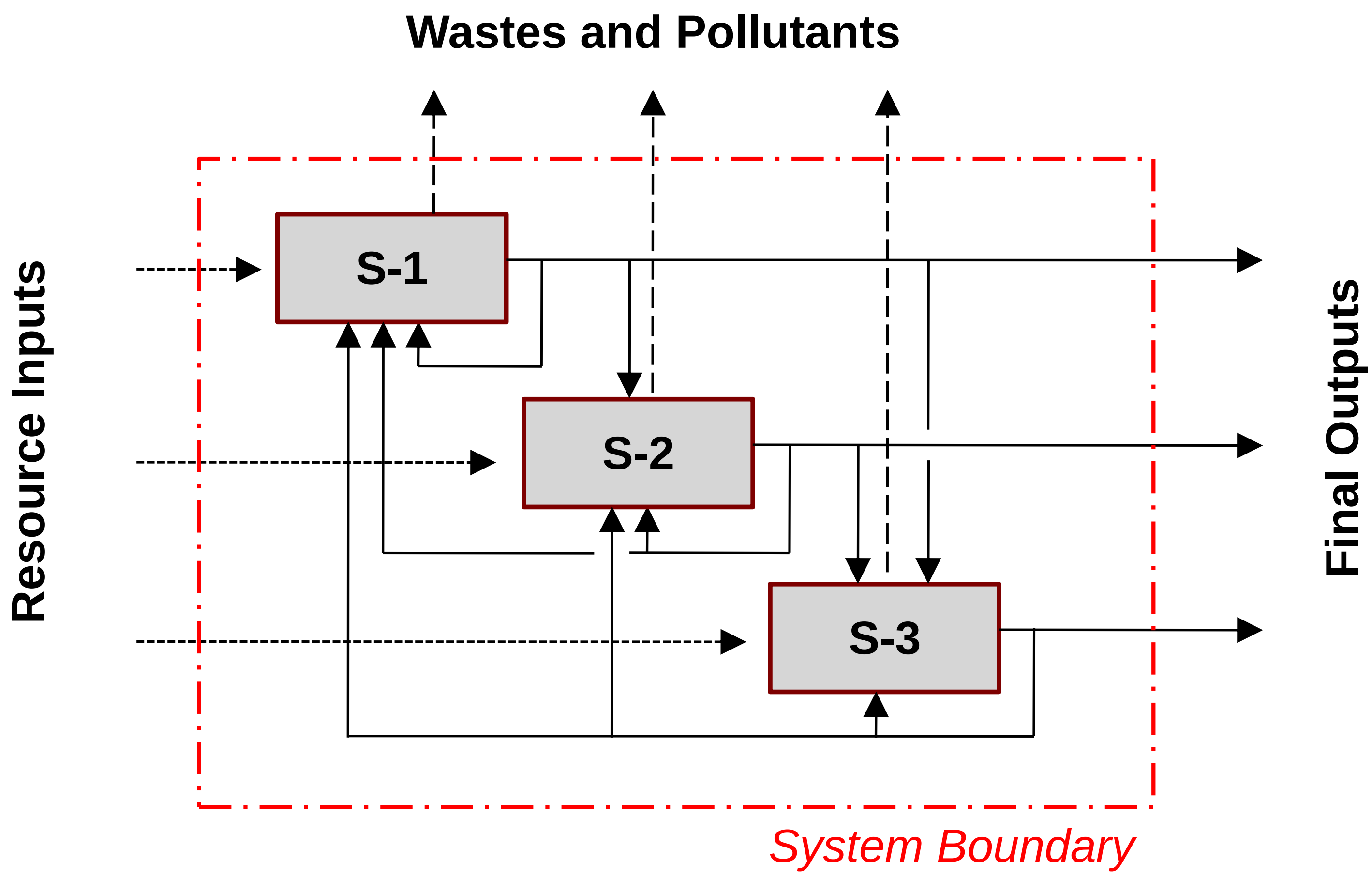
Input-Output Analysis: Historical Perspective



Wassily Leontief received the *Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 1973*

"for the development of the input-output method and for its application to important economic problems"

A Three-Sector Input-Output System



Inoperability Input-Output Analysis

- Haimes and Jiang (2001) defined inoperability as ***"the inability of the system to perform its intended function."***
- Various interpretations of the concept have been proposed:
  - Probability-weighted degree of failure (Haimes and Jiang, 2001)
  - Loss of physical output or functionality (Haimes et al., 2005)
  - **Drop in economic output or demand (Santos and Haimes, 2004; Haimes et al., 2005)**

Important IIM articles

Haimes and Jiang (2001) and Santos and Haimes (2004)

LEONTIEF-BASED MODEL OF RISK IN COMPLEX INTERCONNECTED INFRASTRUCTURES

By Yacov Y. Haimes[1] and Pu Jiang[2]

ABSTRACT: Wassily Leontief received the 1973 Nobel Price in Econo
known as the Leontief input-output model of the economy. Leontief's m
connectedness among the various sectors of an economy and forecasting
in another. A Leontief-based infrastructure input-output model is develope
intraconnectedness within each critical infrastructure as well as the interc
input/output model is then generalized into a generic risk model with the f
A preliminary study of the dynamics of risk of inoperability is discussed, u
Several examples are presented to illustrate the theory and its application

BACKGROUND

The advancement in information technology has markedly increased the interconnectedness and interdependencies of our critical infrastructures, such as telecommunications, electrical power systems, gas and oil storage and transportation, banking and finance, transportation, water-supply systems, emergency services, and continuity of government. There is an urgent emerging need to better understand and advance the art and science of modeling complexity and of interconnected large-scale complex systems; this need stems from the increasing vulnerability of our critical infrastructures.

President Clinton's Executive Order 13010, issued on July 15, 1996, established the President's Commission on Critical Infrastructure Protection (PCCIP) in order to develop a national strategy for protecting these infrastructures from various

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Risk Analysis, Vol. 24, No. 6, 2004

Modeling the Demand Reduction Input-Output (I-O) Inoperability Due to Terrorism of Interconnected Infrastructures[1]

Joost R. Santos[2]* and Yacov Y. Haimes[2]

Interdependency analysis in the context of this article is a process of assessing and managing risks inherent in a system of interconnected entities (e.g., infrastructures or industry sectors). Invoking the principles of input-output (I-O) and decomposition analysis, the article offers a framework for describing how terrorism-induced perturbations can propagate due to interconnectedness. Data published by the Bureau of Economic Analysis Division of the U.S. Department of Commerce is utilized to present applications to serve as test beds for the proposed framework. Specifically, a case study estimating the economic impact of airline demand perturbations to national-level U.S. sectors is made possible using I-O matrices. A ranking of the affected sectors according to their vulnerability to perturbations originating from a primary sector (e.g., air transportation) can serve as important input to risk management. For example,

Overview of Basic IIM
(Haimes and Jiang, 2001)

$$\boldsymbol{q} = \mathbf{A}^*\boldsymbol{q} + \boldsymbol{c}$$

$$\boldsymbol{q} = (\mathbf{I} - \mathbf{A}^*)^{-1}\,\boldsymbol{c}$$

$$\boldsymbol{q} = (\mathbf{I} + \mathbf{A}^* + \mathbf{A}^{*2} + \mathbf{A}^{*3}\ldots)\,\boldsymbol{c}$$

where:

A* = interdependency matrix

c = initial inoperability vector

I = identity matrix

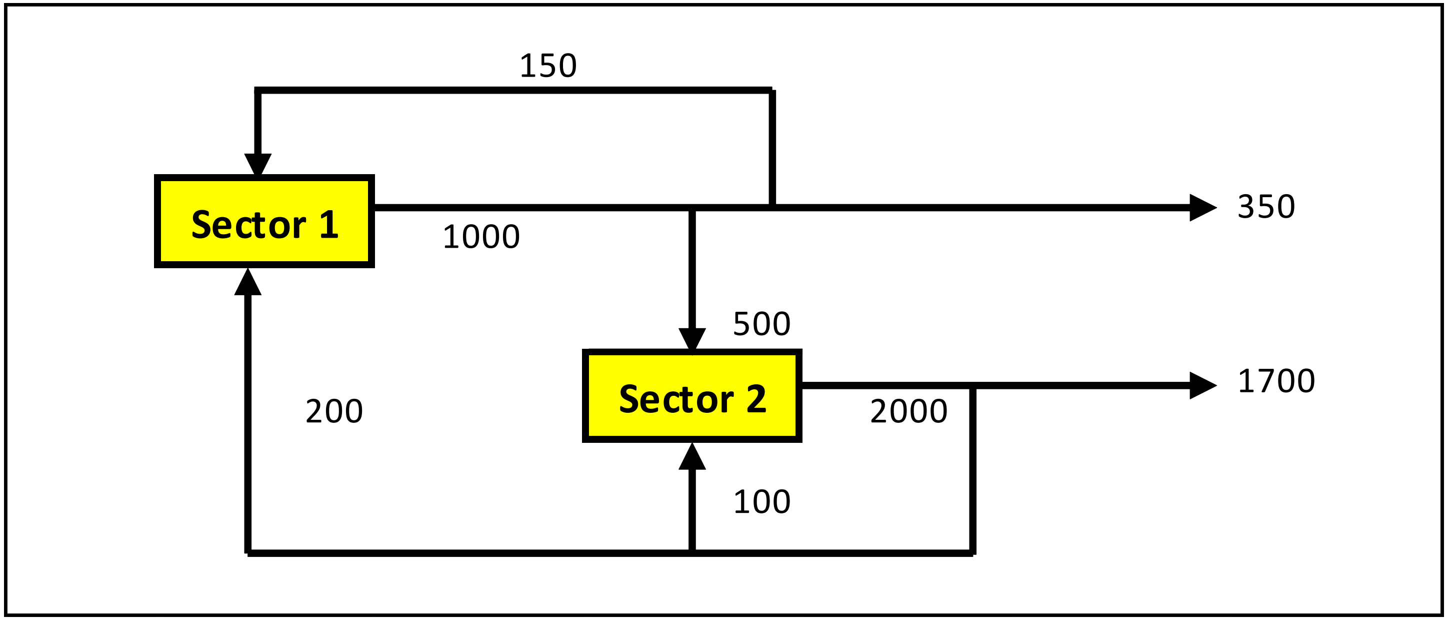
r = risk management resource vector

q = final inoperability vector

IIM Project Components

Project Component	Methodology
Research	➢Development of mathematical framework for MOLP-IIM model
Development	➢Data mining and FGD to calibrate numerical coefficients of working model ➢Coding and preliminary testing of software prototype ➢Drafting of user documentation
Dissemination	➢Release of initial version of MOLP-IIM model ➢Conduct of IIM training workshops for various government agencies ➢Compilation of user feedback for program updates

Baseline Transactions of a Two-Sector Economy (Miller and Blair, 2009)



Baseline Transactions of a Two-Sector Economy

	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	150	500	350	1000
Sector 2	200	100	1700	2000

Baseline Transactions of a Two-Sector Economy

	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	150	500	350	1000
Sector 2	200	100	1700	2000

Sector 1 needs
150 units from Sector 1
and 200 units from Sector 2

Baseline Transactions of a Two-Sector Economy

	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	150	500	350	1000
Sector 2	200	100	1700	2000

Sector 1 produces 1000 units of which
150 units are used by Sector 1
500 units are used by Sector 2
350 units are sold as final product to the consumers

The Input – Output Model

	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	150/1000	500/2000	350	1000
Sector 2	200/1000	100/2000	1700	2000

	Sector 1	Sector 2
Sector 1	0.15	0.25
Sector 2	0.20	0.05

The Input – Output Model

	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	0.15	0.25	350	1000
Sector 2	0.20	0.05	1700	2000

Technical Coefficient Matrix

A

The Input – Output Model

$$Ax + y = x$$

$$y = x - Ax$$

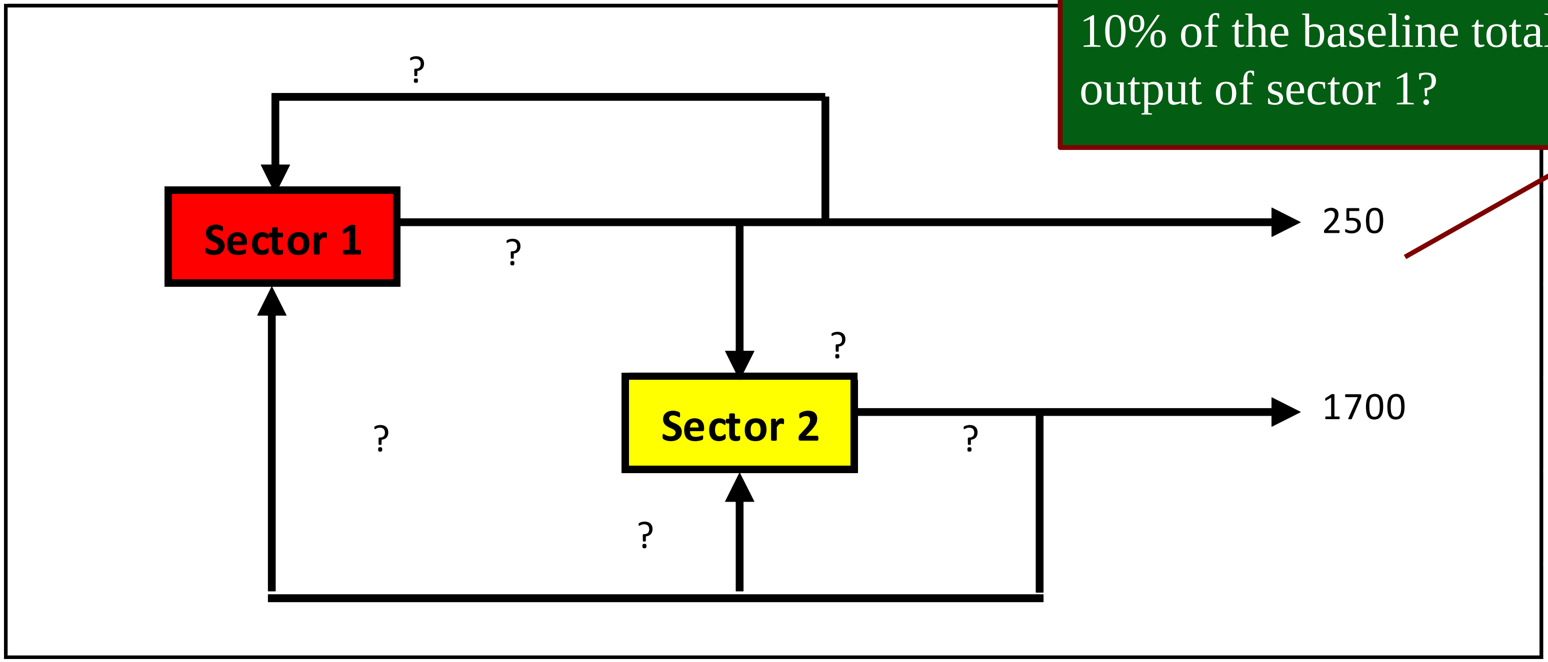
$$y = (I - A)x$$

$$(I - A)^{-1} y = x$$

Leontief Inverse

Transactions for Perturbed Two-Sector Economy

What happens if the final demand for Sector 1 decreases by an amount equivalent to 10% of the baseline total output of sector 1?



Transactions for Perturbed Two – Sector Economy

	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	0.15	0.25	250	?
Sector 2	0.20	0.05	1700	?

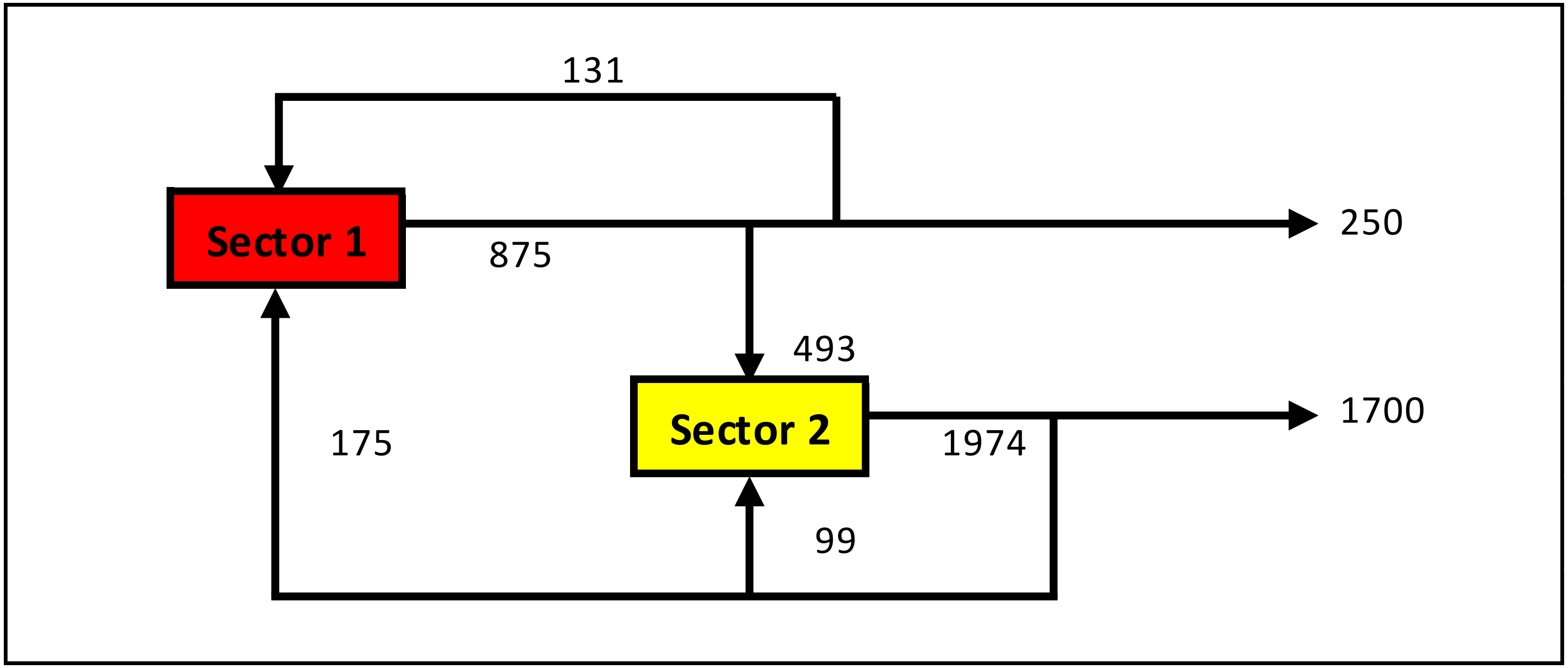
$$A = \begin{bmatrix} 0.15 & 0.25 \\ 0.20 & 0.05 \end{bmatrix}$$

$$(I - A)^{-1} = \begin{bmatrix} 1.25 & 0.33 \\ 0.26 & 1.12 \end{bmatrix}$$

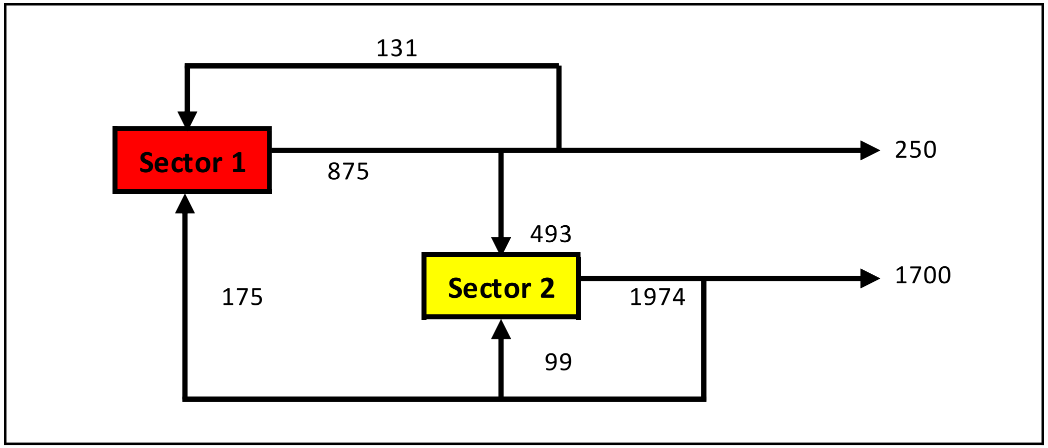
$$(I - A) = \begin{bmatrix} 0.85 & -0.25 \\ -0.20 & 0.95 \end{bmatrix}$$

$$(I - A)^{-1} y = \begin{bmatrix} 1.25(250) + 0.33(1700) \\ 0.26(250) + 1.12(1700) \end{bmatrix} = \begin{bmatrix} 875 \\ 1974 \end{bmatrix}$$

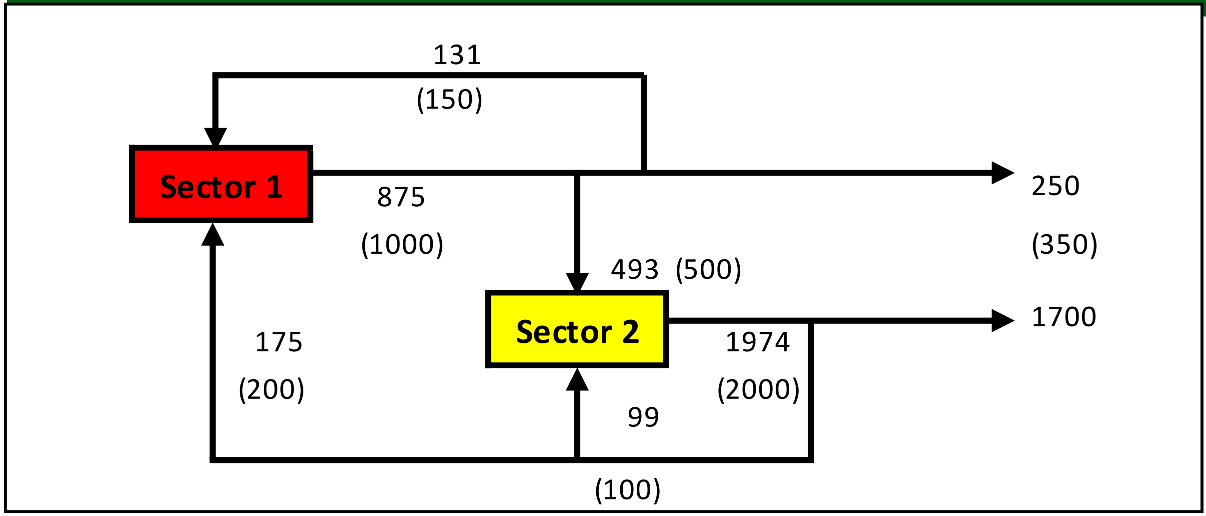
Transactions for Perturbed Two – Sector Economy



Transactions for Perturbed Two – Sector Economy



	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	131	493	**250**	**875**
Sector 2	175	99	1700	**1974**



	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	1.9%	0.7%	10%	12.5%
Sector 2	1.25%	0.05%	0%	1.3%

Reduction in the transactions of the Perturbed Two – Sector Economy

Inoperability Input – Output Model (IIM)

- Utilized for conducting interdependency analysis
- **Inoperability** refers to the level of a system's dysfunction expressed as a percentage of its "as-planned" capacity (Santos and Haimes, 2004; Haimes and Jiang, 2001)
- **Perturbation** refers to a change in the final demand in relation to the "as-planned" final demand
- **Interdependency** refers to the inoperability contribution of one sector to another

Inoperability Input – Output Model (IIM)

$$\mathbf{q} = \mathbf{A^*q} + \mathbf{c^*}$$

$$\mathbf{c^*} = \mathbf{q} - \mathbf{A^*q}$$

$$\mathbf{c^*} = (\mathbf{I} - \mathbf{A^*})\mathbf{q}$$

$$(\mathbf{I} - \mathbf{A^*})^{-1}\,\mathbf{c^*} = \mathbf{q}$$

Where		
	q	the inoperability vector
	A*	the interdependency matrix
	c*	demand side perturbation vector

Inoperability Input – Output Model (IIM)

INPUT – OUTPUT MODEL

$$Ax + y = x$$
$$y = x - Ax$$
$$y = (I - A)x$$
$$(I - A)^{-1} y = x$$

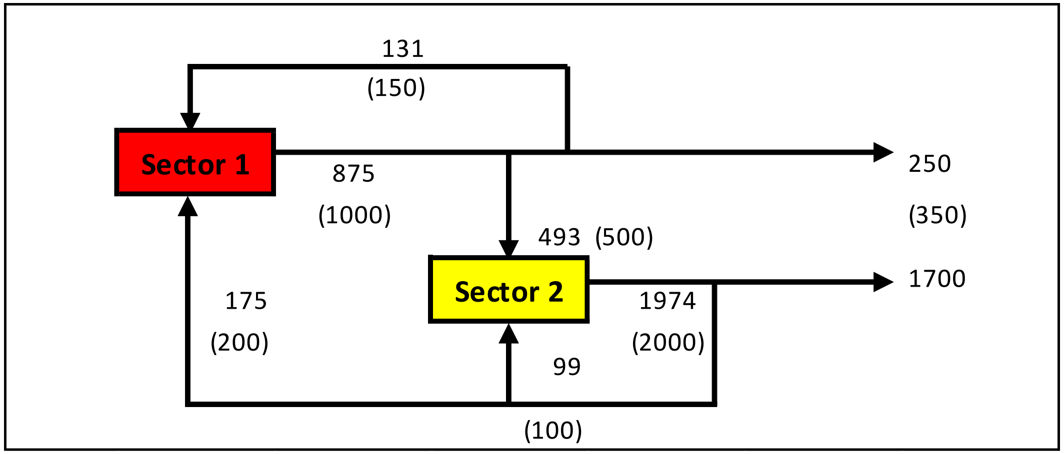
$$q = A^*q + c^*$$
$$c^* = q - A^*q$$
$$c^* = (I - A^*)q$$
$$(I - A^*)^{-1} c^* = q$$

Where

	q	the inoperability vector
	A*	the interdependency matrix
	c*	demand side perturbation vector

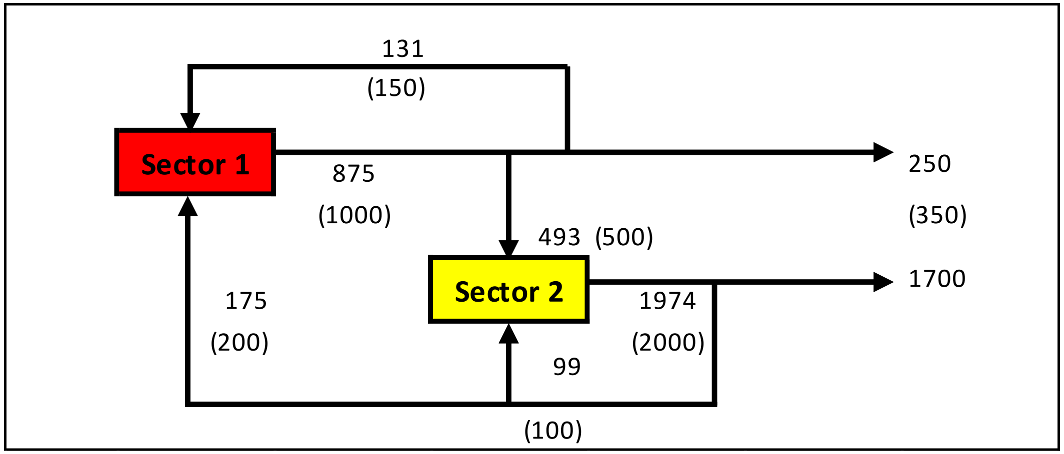
Demand Perturbation

$$c^* = \frac{(\hat{c} - \tilde{c})}{\hat{x}}$$



Where	$\hat{c}$	"as – planned" final demand
	$\tilde{c}$	reduced level of final demand
	$\hat{x}$	"as-planned" total production

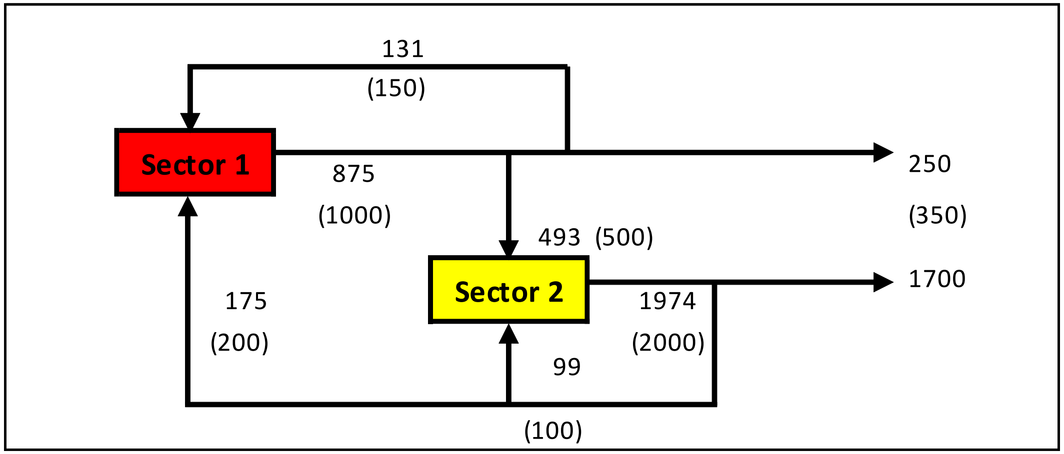
Demand Perturbation



$$c^* = \frac{(\hat{c} - \tilde{c})}{\hat{x}}$$

$$c^* = \begin{bmatrix} \frac{(350 - 250)}{1000} \\ \frac{(1700 - 1700)}{2000} \end{bmatrix} = \begin{bmatrix} 0.10 \\ 0 \end{bmatrix}$$

Inoperability Vector

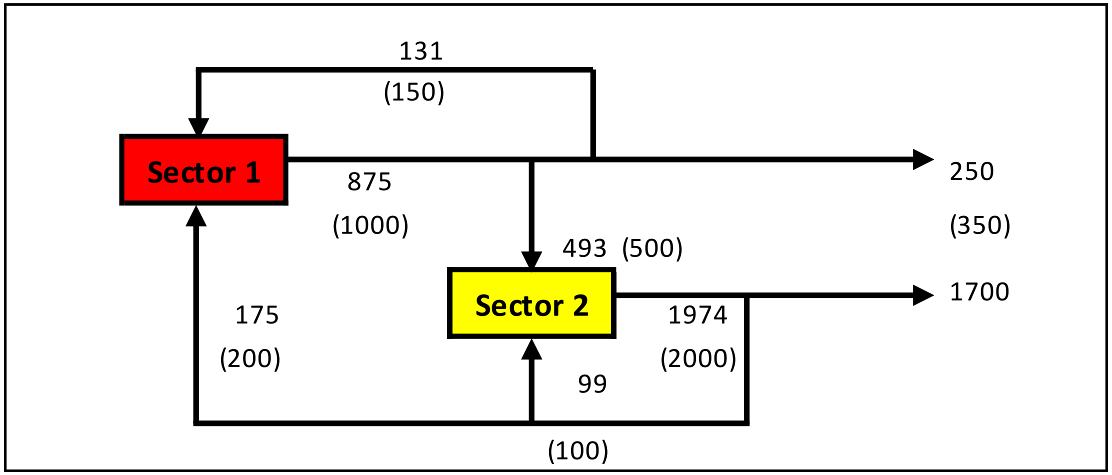


$$\mathbf{q} = \frac{(\hat{x} - \tilde{x})}{\hat{x}}$$

Where

	$\mathbf{q}$	the inoperability vector
	$\hat{x}$	"as – planned" total output
	$\tilde{x}$	reduced level of production

Inoperability Vector



$$\mathbf{q} = \frac{(\hat{x} - \tilde{x})}{\hat{x}}$$

$$q = \begin{bmatrix} \frac{(1000 - 875)}{1000} \\ \frac{(2000 - 1974)}{2000} \end{bmatrix} = \begin{bmatrix} 0.125 \\ 0.013 \end{bmatrix}$$

Interdependency Matrix

	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	0.15	0.25	350	1000
Sector 2	0.20	0.05	1700	2000

$$\mathbf{A^*} = \frac{a_{ij}\hat{x}_j}{\hat{x}_i}$$

Where

$\mathbf{a_{ij}}$ technical coefficient of matrix A

$\hat{x}_i$ "as-planned" total output of sector i

$\hat{x}_j$ "as-planned" total output of sector j

Interdependency Matrix (A*)

	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	0.15	0.25	350	1000
Sector 2	0.20	0.05	1700	2000

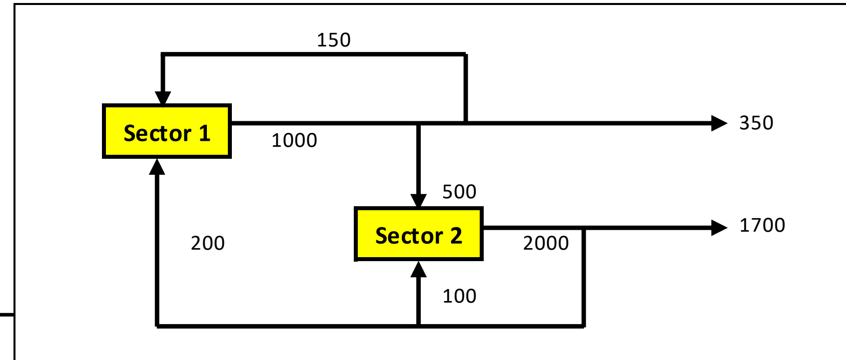
	Sector 1	Sector 2
Sector 1	$\frac{0.15(1000)}{1000}$	$\frac{0.25(2000)}{1000}$
Sector 2	$\frac{0.20(1000)}{2000}$	$\frac{0.05(2000)}{2000}$

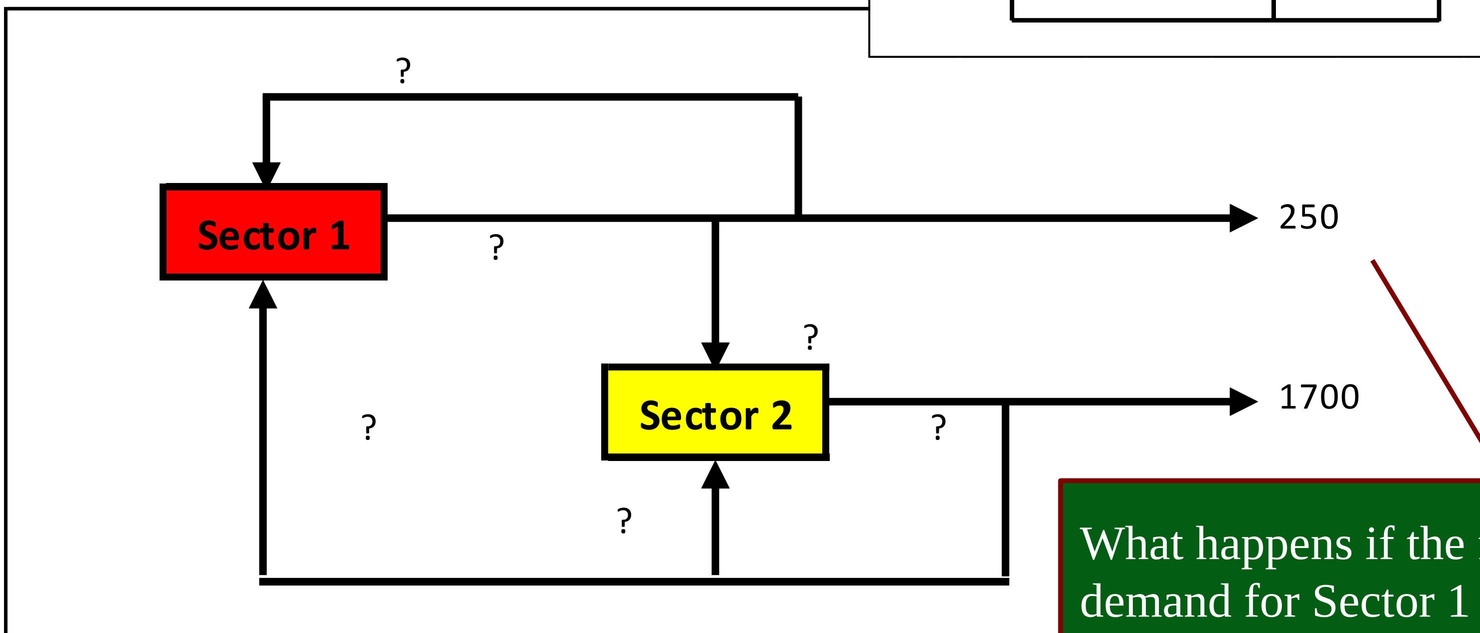
Interdependency Matrix (A*)

	Sector 1	Sector 2	Final Demand (y)	Total Output (x)
Sector 1	0.15	0.25	350	1000
Sector 2	0.20	0.05	1700	2000

	Sector 1	Sector 2
Sector 1	0.15	0.50
Sector 2	0.10	0.05

Transactions for Perturbed Two-Sector Economy





What happens if the final demand for Sector 1 decreases by an amount equivalent to 10% of the baseline total output of sector 1?

IIM Case Study

	Sector 1	Sector 2	Demand Perturbation (c*)	Inoperabilty Vector (q)
Sector 1	0.15	0.50	**0.10**	**?**
Sector 2	0.10	0.05	0	**?**

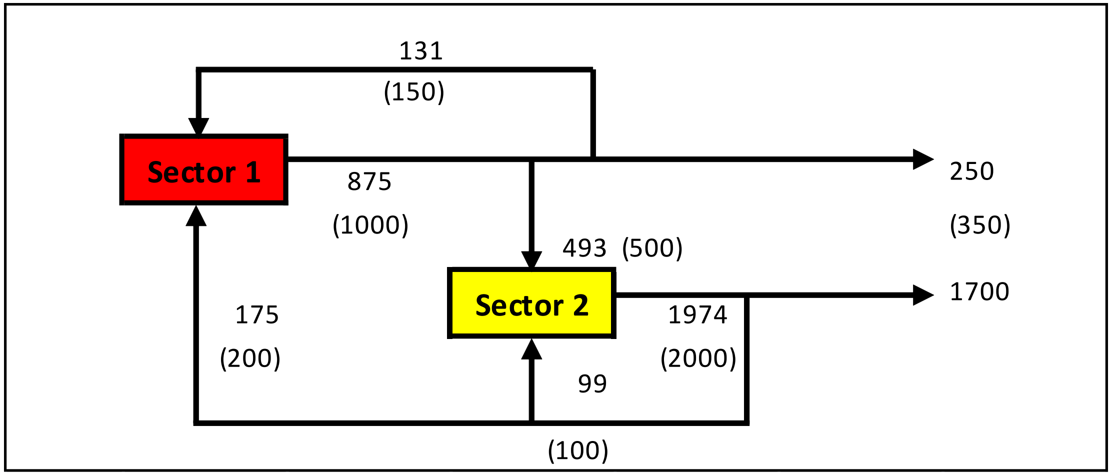
$$A^* = \begin{bmatrix} 0.15 & 0.50 \\ 0.10 & 0.05 \end{bmatrix}$$

$$(I - A)^{-1} = \begin{bmatrix} 1.25 & 0.66 \\ 0.13 & 1.12 \end{bmatrix}$$

$$(I - A^*) = \begin{bmatrix} 0.85 & -0.50 \\ -0.10 & 0.95 \end{bmatrix}$$

$$(I - A)^{-1} c^* = \begin{bmatrix} 1.25(0.10) + 0.66(0) \\ 0.13(0.10) + 1.12(0) \end{bmatrix} = \begin{bmatrix} 0.125 \\ 0.013 \end{bmatrix}$$

IIM Case Study



	Sector 1	Sector 2	Demand Perturbation (c*)	Inoperability Vector (q)
Sector 1	0.15	0.50	**0.10**	**0.125**
Sector 2	0.10	0.05	0	**0.013**

Conclusion

- Connectivity within an economic system means that the total damage done in the aftermath of a disaster is much larger than the initial direct damage

Acknowledgments

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Thank you!

Questions and Comments are Welcome