Assessing Economic Impacts of Infrastructure Disruptions

Comparison of Input/Output and System Dynamics Approaches

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Summary

Purpose

The Critical Infrastructure Protection Decision Support System is a research program of the United States Department of Homeland Security whose goal is to inform decisions regarding infrastructure protection, with special consideration of infrastructure interdependencies. Possible economic impacts of infrastructure disruptions are an important metric for comparing alternative mitigations. Leontiff Input/Output (I/O) methods have been suggested and used for estimating these impacts. We have developed a simple model in Vensim to help our customers explore and understand possible differences between I/O and System Dynamics (SD) formulations, and the mitigating measures their results suggest.

Approach

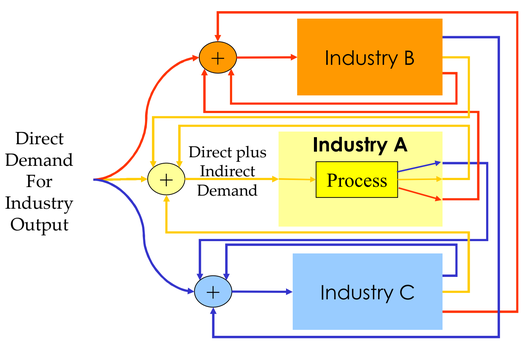
- Build a simple SD model of interactions between economic sectors that is consistent with a static I/O model.
- Include the basic internal dynamics of each sector to focus on the effects of the production dynamics that the I/O formulation necessarily leaves out. Other important processes (e.g. price substitutions, induced effects in households) are omitted here because they can be wrapped around both I/O and SD formulations.
- Compare the assessed impacts for diverse disruptions.

Results

- The model allows prospective decision-makers to quickly compare estimates of economic impact resulting from infrastructure disruption using two alternative models.
- A simple SD representation of sector production:
  - Contains clear infrastructure linkages. Such linkages don't exist in the I/O formulation;
  - Exposes processes that can buffer, amplify, and delay the costs of disruptions in contrast to the I/O model's local equilibration response;
  - Allows the user to see the effectiveness of simple mitigations (e.g. strategic stockpiling) that can't be represented in the I/O formulation;
  - Can change economic impact estimates significantly

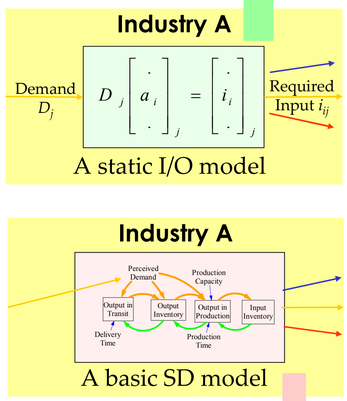
Economic Feedbacks

Direct demand for industry output creates demand for input from other industries

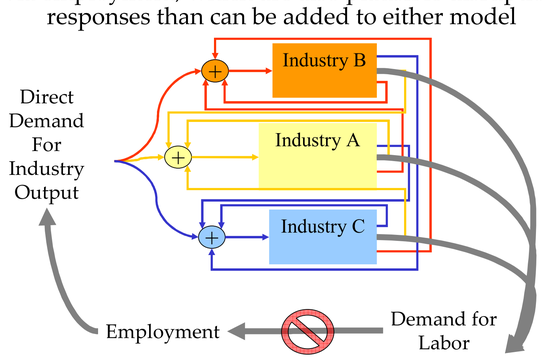


These inter-industry feedbacks can amplify local perturbations, including perturbations caused by disruptions to infrastructures

We compare two alternative models of industry processes, focusing on the economic effects of disruptions calculated by each model



To clarify comparison we have not included changes in production functions or changes in final demand via employment, which are also plausible disruption responses than can be added to either model



Input/Output Model

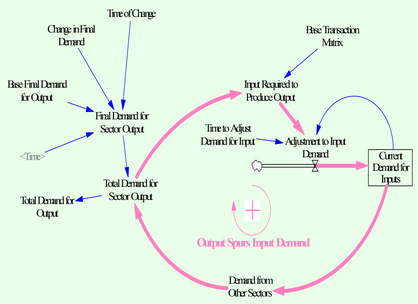
- The fundamental input is a technology matrix **M**: the purchases of each sector *j* from each sector *i*
- **M** is scaled to produce the direct requirements matrix **A**: the input from each sector *i* required to create a unit output from sector *j*
- A change in final demand $\mathbf{D}_0$ creates a demand for additional intermediate inputs $\mathbf{D}_i$:

$$\mathbf{D}_i = \mathbf{A}\mathbf{D}_0$$

- Producing these inputs creates additional demands, which require additional inputs, and so on. The total economic impact includes all direct and indirect effects of the additional demand:

$$\mathbf{T} \equiv \mathbf{D}_0 + \mathbf{A}\mathbf{D}_0 + \mathbf{A}^2\mathbf{D}_0 + \ldots = \left[\mathbf{I} - \mathbf{A}\right]^{-1}\mathbf{D}_0$$

The I/O model is static. It captures the long run equilibrium effect of feedbacks among economic sectors. We can make an analogous SD representation by assigning a finite time for indirect effects:



Key Assumptions

- There are no constraints on production capacity
- Production process is captured in the fixed production factors of the matrix **A.** Process dynamics are fast compared to system perturbations.
- The time for indirect effects to propagate is small compared time frame of interest.

These assumptions may not be appropriate for systems responding to sudden infrastructure disruptions

Including Capacity Constraints

- The total economic activity associated with a desired final demand of **O** is:

$$\mathbf{T} = \left[\mathbf{I} - \mathbf{A}\right]^{-1}\mathbf{O}$$

- Suppose the available capacity in each sector is given by **C**. The maximum activity level in each sector is then:

$$\mathbf{T}^* = \begin{bmatrix} \cdot \\ t^*_i = \min(t_i, c_i) \\ \cdot \end{bmatrix}$$

- And all activities must be curtailed to meet capacity limits:

$$\mathbf{O}^* = \mathbf{O} \bullet \min_i \left\{ \frac{t_i - t^*_i}{t_i} \right\}$$

- So that the shortfall **L** in final output is:

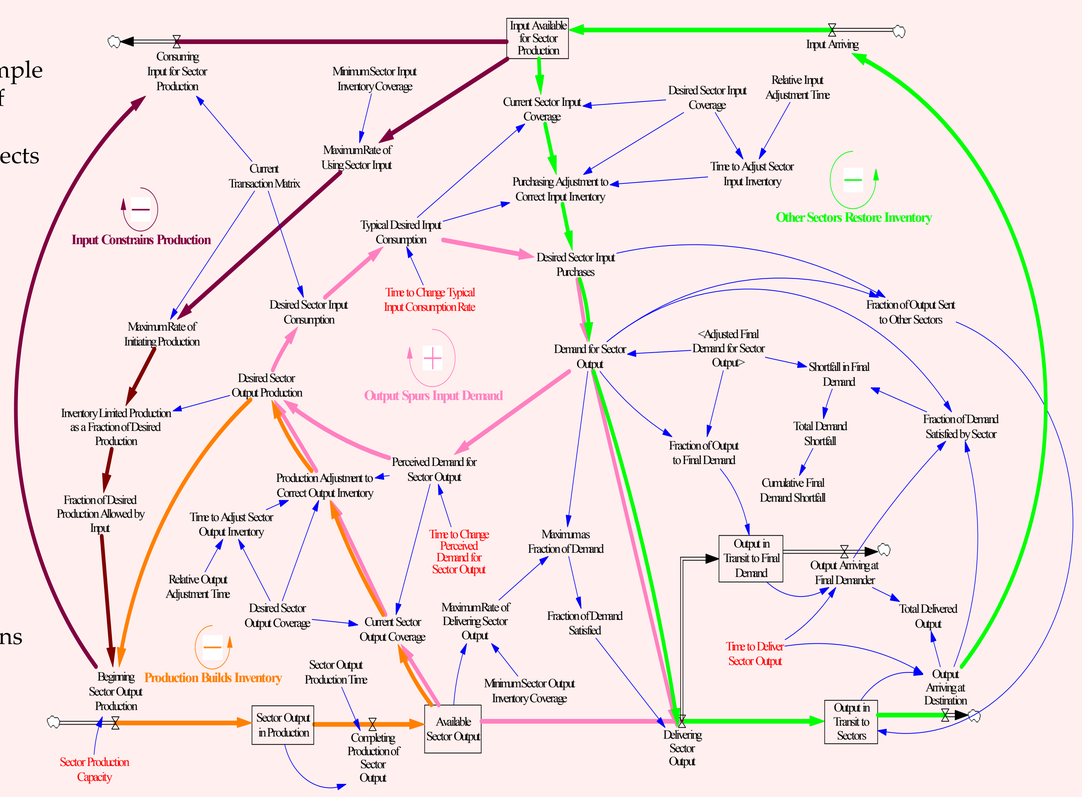
$$\mathbf{L} = \mathbf{O} - \mathbf{O}^*$$

Simple Process Dynamics Model

We've defined a very simple generic representation of production dynamics to illustrate the possible effects of:

- Inventories of sector outputs and inputs
- Production time
- Transportation time
- Information flows
- Production capacity constraints

on estimated economic losses following infrastructure disruptions



Common Model Elements

For consistency, the SD model uses the requirements matrix **A** from the I/O model to determine the industries' production functions

Disruptions to power and telecommunications can reduce a sector's production capacity. These effects can be captured in both the extended I/O and SD models

Infrastructure disruptions can be naturally represented using parameters of the simple SD model:

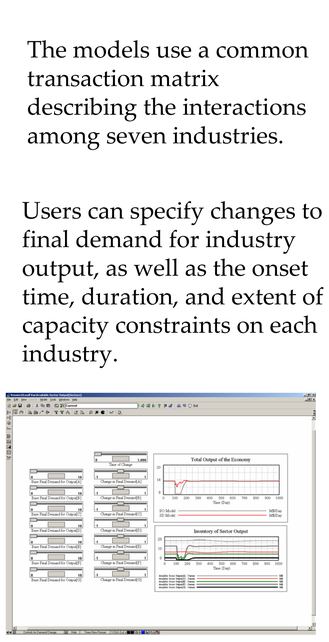
- Transportation – increased delivery time for outputs
- Telecommunications – increased information delays

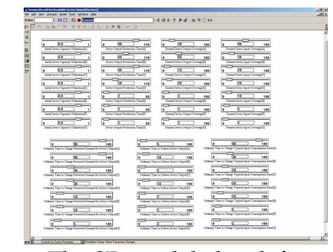
Implementation and Results

The simulator interface lets the user describe the system and impose perturbations

The models use a common transaction matrix describing the interactions among seven industries.

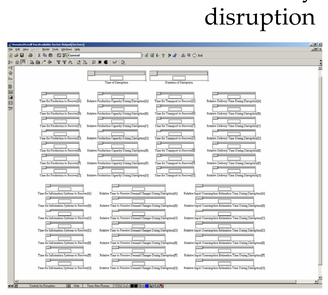
Users can specify changes to final demand for industry output, as well as the onset time, duration, and extent of capacity constraints on each industry.





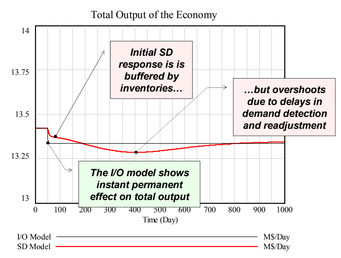
The SD model also defines diverse time constants…

… which can be altered by disruption

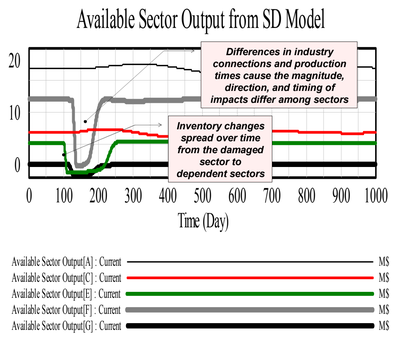


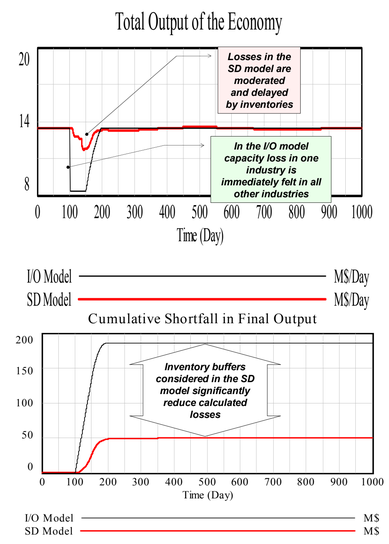
Estimated impacts using the I/O and SD models can then be compared. Example perturbations include:

A) **Reduction in final demand** in a sector is a typical application of an I/O model. The SD model shows the potential impacts of buffers and delays as we approach a new equilibrium.

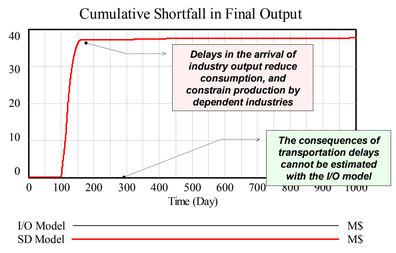


B) **Temporary capacity loss** in a single industry propagates to other industries





C) **Transportation delays** for the output of a single industry can have high costs. Here we've doubled the transport time for an industry's output during disruption



Including production process dynamics, even in a very simplified and stylized way, leads to estimates of economic impacts that can differ from corresponding I/O estimates by as much as the size of the impact.

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