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Modeling Economic Impacts to Critical Infrastructures in a System Dynamics Framework

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Abstract

Our paper presents a model of economic impacts arising from disruptions to critical infrastructures. This model is a component of the Critical Infrastructure Protection Decision Support System (CIP/DSS) which simulates the dynamics of a set of interconnected individual infrastructures. We use factors of production (such as energy, telecommunications, and labor) from the CIP/DSS model to estimate the effects of interruptions to these infrastructures. The system dynamics approach we use is compared to equilibrium-based approaches such as input-output modeling. Our method allows an understanding of the economic benefits of various protective measures. We incorporate non-equilibrium dynamics that arise from infrastructure disruptions to evaluate economic impacts such as lost revenues and lost sales. The results from a disruption due to an infectious disease outbreak are presented. We show that imposition of quarantine on a metropolitan area creates large economic impacts as compared to other mitigative strategies.

Key words: *economic impact; critical infrastructure; dynamic non-equilibrium model.*

Introduction

Modeling economic impacts arising from disruptions to critical infrastructures is increasingly important for determining the most effective investment strategies for protective measures and loss mitigation if a disruption event occurs. While many mitigation measures may appear important and potentially cost-effective under certain circumstances, most government agencies, including the Department of Homeland Security, need to rank these alternatives to effectively allocate their limited budgets. To rank these preventative measures, the economic costs and potential savings (reductions in lives lost or economic activity losses) need to be evaluated. It is also necessary to understand costs for the entire economy—beyond those of the initially impacted infrastructures—to fully comprehend the magnitude of the event and to make the appropriate allocation decisions.

* The authors would like to thank the entire CIP/DSS project team at Argonne, Los Alamos, and Sandia National Laboratories. We are particularly grateful to Sam Flaim, Dennis Powell, and the anonymous reviewers for their valuable suggestions and comments.

The economic impacts modeled in a system dynamics framework are built upon a collection of individual models of interdependent critical infrastructures (sectors). Dynamics of a sector are a function of the operations in that sector as well as operations in other infrastructures. The model uses these interactions and additional information to estimate total direct economic impacts from an incident. Our approach allows us to estimate impacts to the economy represented as a dynamic system without requiring the assumptions of equilibrium solutions. In fact, economic impacts arising from disruptive events are perhaps better described as effects caused by disequilibrium dynamics.

The first section of the paper describes the methodology used for estimation of the economic impacts to the critical infrastructure models. The next section contains an overview of the Critical Infrastructure Protection Decision Support System (CIP/DSS)[1] Metropolitan Model. We continue with a summary of the economic model itself. We close with results from a biological scenario simulation.

Methodology

The key feature of our model is its dynamic nature. We model the disruptions as they occur and propagate through the infrastructures. There are a number of interdependencies between infrastructures. For example, the banking and finance sector performance depends on the availability of telecommunications, energy, and labor force; emergency response depends upon roads, transportation, and telecommunications availability; food availability depends on agriculture and energy as well as other sectors; etc. Therefore, even if a system was in equilibrium at the beginning of a scenario, because of the initial disruption and interactions between different sectors illustrated above, we do not expect that the system will go through a set of equilibrium states during a scenario. Thus the goal is to investigate and understand the non-equilibrium, non-linear dynamics of the system.

Our system dynamics (SD) model with multiple feedback structures is well suited for such a task. This is a point of departure from the input-output (I/O) approaches where equilibrium conditions are implied. However, during a disruptive event there are no apparent reasons why the equilibrium, as it is normally defined in economics, should occur. In general the incidents that are modeled by this system are transient in nature, often lasting no longer than a few weeks. I/O models are most often calibrated to annual data and intend to capture permanent changes and long term trends, smoothing out short term dynamics.

The dynamic nature of our approach allows us to model the impacts as they occur in individual infrastructures. For example, if an event were to occur initially in one infrastructure, our model would simulate the impact to that infrastructure and its effect on

[1] *The CIP/DSS project is a joint effort of Argonne National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories, sponsored by the Science & Technology Directorate of the U.S. Department of Homeland Security.*

other infrastructures in the system. Additionally, those secondarily affected infrastructures would further propagate the effects into other infrastructures as well as back into the initially affected infrastructure through feedback loops present in the system. Generally, a static equilibrium model, such as an I/O model employs externally calculated primary economic effects to estimate total economic impacts by using I/O multipliers. The difference between these two approaches is illustrated in Figure 1 below.

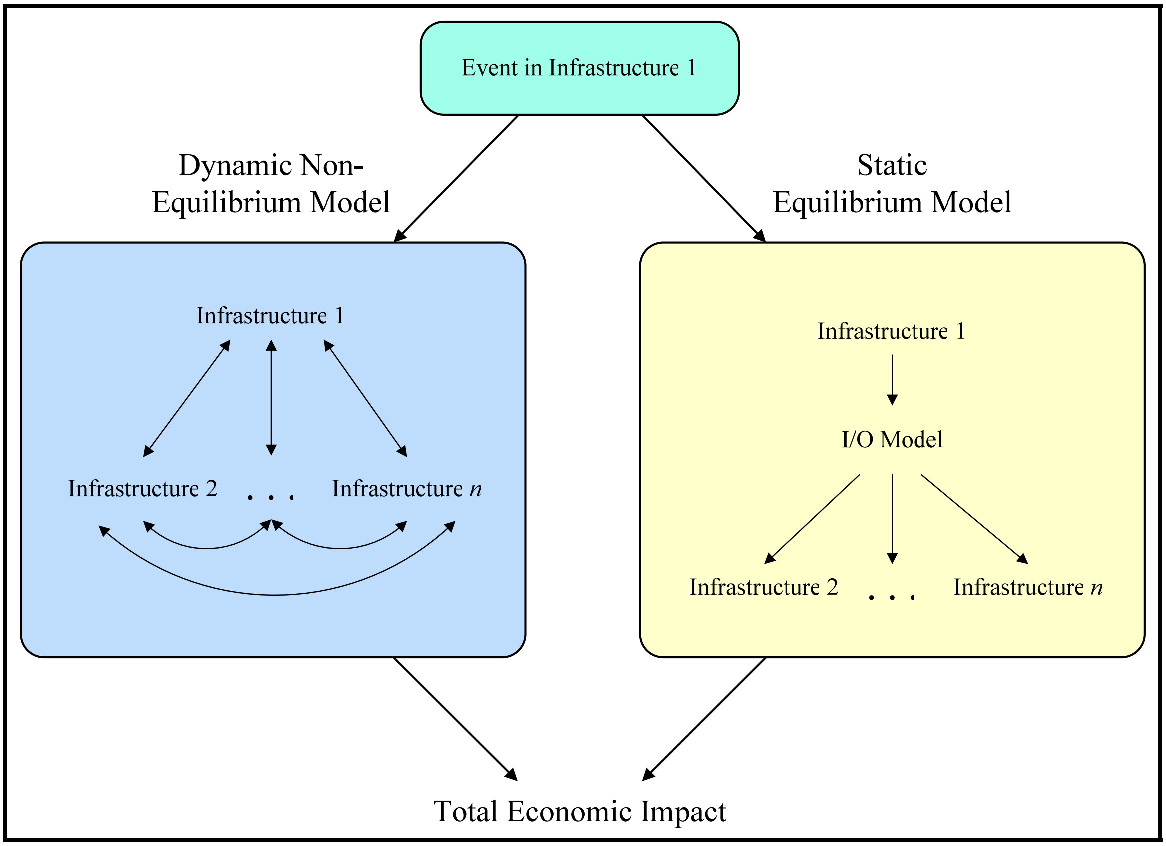

Figure 1. Event Propagation in Dynamic Systems vs. I/O Model

To estimate economic impacts, we simulate initial physical disruptions to individual models of critical infrastructures. These disruptions then translate into the primary economic impacts on those infrastructures and propagate into other infrastructures to generate secondary economic impacts. From those calculations we derive the estimates of total direct economic impact—the sum of primary and secondary impacts. This differs from I/O approaches that require external estimation of primary impacts—expressed in monetary terms—in order to estimate the economic consequences.

Our model also takes into account that the total economic impacts depend on specific mitigative measures taken prior or during a particular event. This approach allows us to evaluate and rank protective measures and response strategies. For example, we can simulate the release of a contagious disease and evaluate the economic impacts from different vaccination strategies.

An additional non-equilibrium component of our approach is the ability to explicitly model the population's response to events. We model behaviors such as hording and latent demand. These behaviors are non-equilibrium in nature and may not be suitable for modeling in equilibrium-based tools.

To estimate the economic effects we explicitly acknowledge that the state of the infrastructure within a certain area affects commerce and production within that area. Some of the main factors affecting commerce and production are: energy and telecommunications availability, transportation, labor force, etc. All of these are factors of production—contributing to either capital or labor components required for production or commerce to transpire.

Our treatment is consistent with the Cobb-Douglas production functions, where capital and labor are the main determinants of production. The general form for the Cobb-Douglas production function is:

$$q = aK^{\alpha}L^{\beta}$$

where K is capital and L is labor. We do not attempt to calculate the capital directly, but instead use the factors of production listed above and their relative changes to estimate the relative reduction in capital due to an event. We assume that reductions in capital are proportionate to a multiplicative function combining relevant factors of production. Future analysis of relevant data may improve this functional form. The labor component is modeled directly in the SD model.

We implemented this approach in the SD model by using the relative reductions in available capital and labor to estimate the productivity or commerce lost. Incomplete employment of existing factors of production may arise because of scenario events, such as road congestion and quarantine (and thus the labor not being able to reach the work places), shortfalls in electricity available, damaged telecommunications system, etc. We separately calculate the losses resulting from permanent labor and capital reductions, such as labor population reduction or destruction of productive capabilities as a result of scenario events. Using this approach we can calculate reduction in sales and value-added for the economy.

Critical Infrastructure Model

The CIP/DSS Metropolitan Model is a set of critical infrastructure subsectors modeled in a system dynamics framework using Vensim. The goal of the Metropolitan Model is to represent the interdependencies between infrastructures and simulate the disturbances that can start in one infrastructure and propagate to others. Every infrastructure—also called a sector—consists of a set of subsectors that represent the major portions of that sector. For example, the electricity subsector—a component of the Energy sector—models the generation, distribution, and consumption of electricity. It also models revenues and costs in additional to possible shortages of supply related to demand-rationing decisions.

Each sector models the broad capabilities of the infrastructure and is not intended to be a stand-alone, detailed model. Instead its strengths lie in the representation of first order interactions between sectors and the ability to model/show how a simple disruption in one sector can propagate to others and disrupt the entire system of critical infrastructures. To illustrate this, the Figure 2 below represents the interdependencies in the infrastructure model from a scenario involving the release of an infectious disease. Effects spread through the population not only from initially and secondarily infected people, but through self and mandatory quarantine. Effects also spread into other sectors as less people use transportation to get to work and to shop. Public Health and Emergency Services experience increased demand as people seek medical treatment for the disease. Similar effects can be observed in other scenarios as one event spreads through many different sectors.

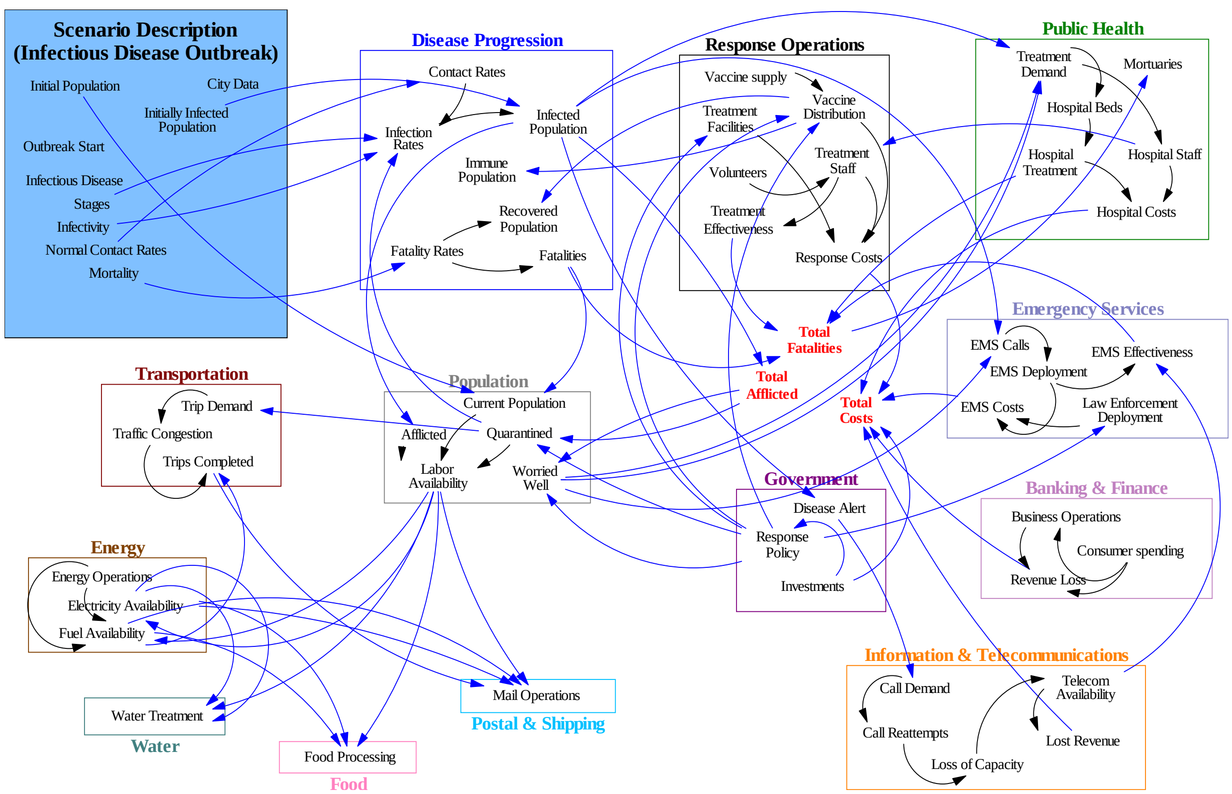

Figure 2. Influence Diagram for an Infectious Disease Outbreak

The primary responsibility for development of the Metropolitan CIP/DSS Model is at Los Alamos National Laboratory. The National CIP/DSS Model is developed by Sandia

National Laboratories. Argonne National Laboratory's main task is the Decision Support System, which is used to rank outcomes of the different scenarios and studies.[2]

Economic Model

The economic sector model is currently set up to do two main tasks: aggregate costs already in other infrastructures and estimate the impact to economic sectors outside the DHS-defined critical infrastructures. The aggregation in the economics model is to provide appropriate level data for the decision support system, although non-aggregated elements are available for more detailed analysis. Before the introduction of this model, post-processing calculations where performed to derive these numbers.

Initial sector impacts from an incident are calculated in the individual sectors with interdependencies modeled to produce secondary effects in other sectors. Most sectors compute revenue and other losses due to clean-up, repairs, rebuilding, etc. Other sectors, such as the Energy subsectors, contain further information to give baseline revenue values with or without an incident. All of the metrics are passed into the economic sector model for further computation.

Estimation of impacts to the rest of the economy is still in its early stages. Currently, lost value-added, lost sales, and lost wages for each of the North American Industry Classification System (NAICS) supersectors are calculated to estimate these costs. (See Figure 3 below for a view of this model.) Value-added is a measure of productivity in an industry. It is more conservative than lost sales or revenues since lost sales are often only temporary—they can be recovered within a short period time after and incident. Lost value-added tends to be irrecoverable over short periods of time and is therefore a more accurate measure of the economic losses due to temporary disruptions.

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[2] Although these are the primary roles of each national laboratory, the process is integrated and all responsibilities are shared across the labs.

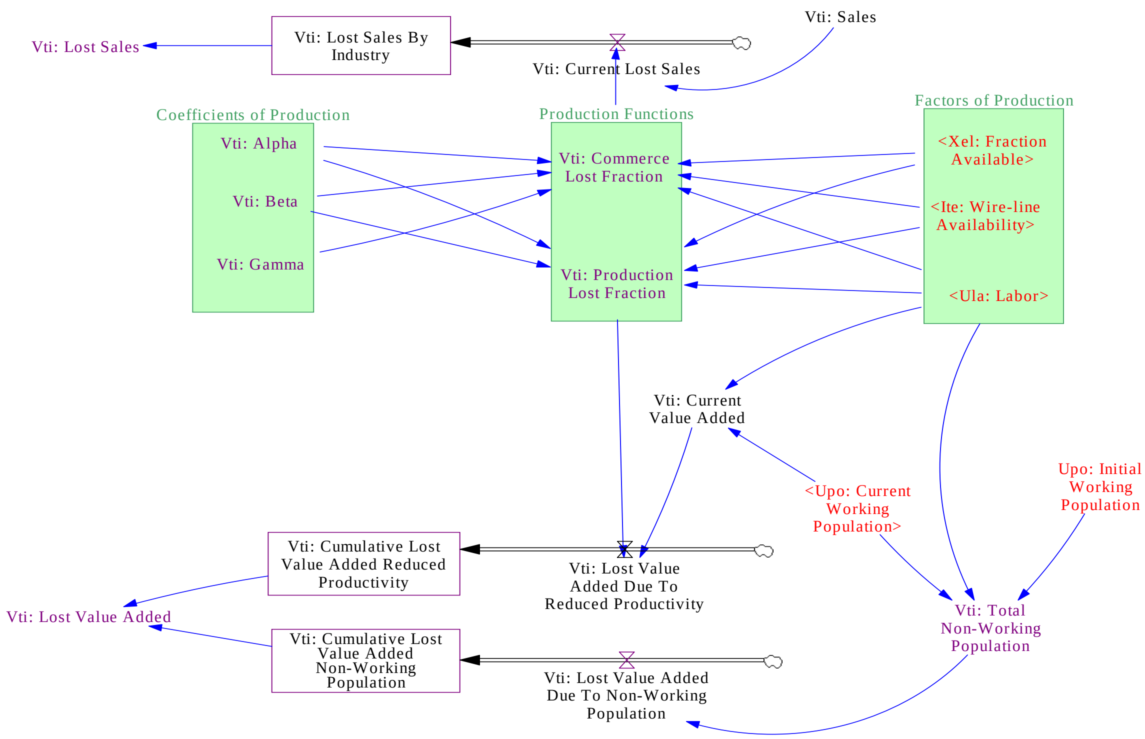

Figure 3. Representation of the Total Impact Subsector of the Economic Model

The value-added lost computation is made using the gross state product and employment by sector available from the Bureau of Economic Analysis. Assuming a 5-day work week with holidays, we estimate a 230-day work year to calculate gross state product per worker per day (value-added per worker per day) for each industry. We then estimate the dollar value lost for absent workers due to death or illness or quarantine, for example. We separately compute the lost value from reductions in productivity using inputs of energy, transportation or telecommunications—which are all output variables from other metropolitan infrastructures. These two values are then added together to produce our total lost value-added from an incident. This calculation is completed for every time step in the scenario. This method enables a dynamic computation that takes into account the current state of the model without additional equilibrium assumptions.

Lost sales, although it can be an over-estimation of long term impacts, is still an important measure; they reflect the opportunity costs incurred by the industry. The economic model calculates these—independently from similar calculations in the individual infrastructure models—using data from the 2002 Economic Census. While the individual sectors use unit calculations and other similar methods, the economic model uses the production function from inputs (energy, transportation, labor, etc.) as explained in the methodology section of this paper. These two methods help to provide slightly different perspectives given that the infrastructure sectors and the NAICS industries do not always map directly to each other. This enhances the overall economic impact calculations. As with the value-added calculations, sales are dynamically computed for all time-steps in the scenario.

In the future, the economic model will be expanded to include other important economic indicators for a major event. We are currently refining the wages and personal income loss calculations in the model. Based on those, lost income taxes can be computed to give another estimate of government receipts losses (other than the sales tax losses we currently have). Commercial and residential property values and losses (perhaps by square footage lost) are another important impact in many scenarios and would be valuable to compute in the model.

Results

The results explained below are derived from several scenario runs of the CIP/DSS Metropolitan and National models combined. The first scenario was the base comparison model in which no incident had occurred. It was run for the same representative city of five million people as well as the same time and date as the incidents. This scenario is entitled "Base Readiness" in the results below. "Base Incident" refers to the run in which an infectious disease is released (at time = 100 hours) and 1000 people are initially infected but no other mitigating factors (such as bio-detection systems or required quarantine) are used. The last scenario for which we show results is the "Quarantine Incident" in which the original parameters for the incident are used, except that a mandatory quarantine for a large percent of the population is enacted. While other alternative scenarios were run in our study, the most interesting economic results can be explored with these scenarios.

Sensitivity analyses were performed on all of the alternatives investigated. This was accomplished by identifying a number of key variables that significantly affect the outcomes and by running a number of simulations (625 for each of the scenarios) varying those key variables with a uniform distribution in pre-determined ranges[3]. The results of the sensitivity runs are consistent with the relative comparisons of the point case results presented here.

The results from the various scenario runs (shown in figures 5-8 below) demonstrate that the quarantine imposed (self or mandatory) on people in the metro area produces the majority of the economic losses. In the base incident, quarantine at its peak affects approximately 50% of the population. The incident with quarantine has at its peak 95% of the population quarantined (see Figure 4)[4].

[3] See Fair at. al. (2005) for more details on the sensitivity analysis.
[4] The fraction of people quarantined in the model is an estimate of the population's response to an event of this type. However, there is a significant amount of uncertainty in these estimates and there is little or no relevant historical data.

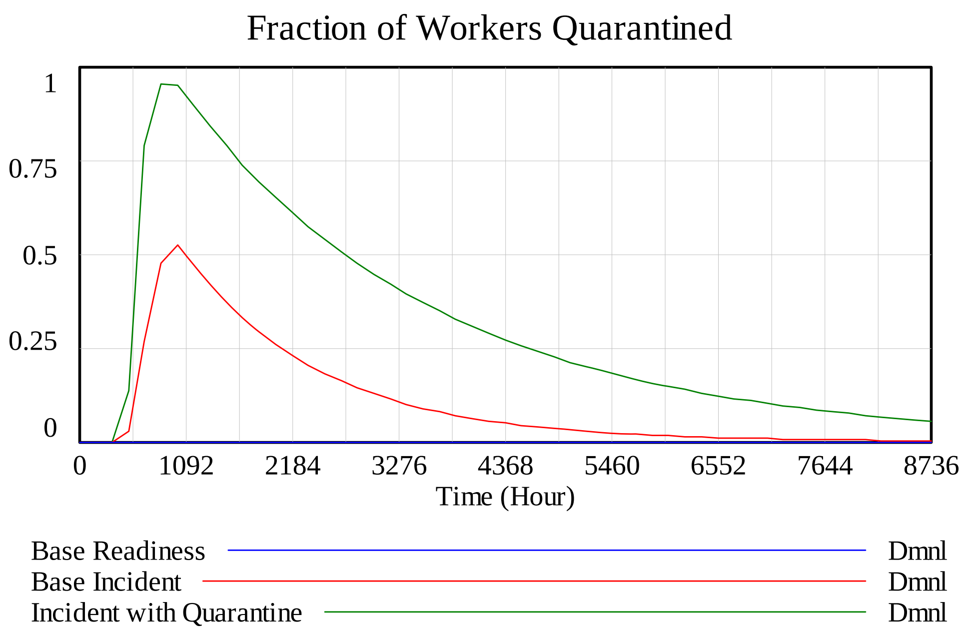

Figure 4. Fraction of Workers Quarantined

The total revenue and revenue losses calculated in the economics sector are produced by adding the respective calculations from the other sectors—although not all sectors perform this calculation. Lost revenue from the incident with quarantine totals just over $18 billion dollars[5] (see Figure 5). Most of these losses (over $17 billion) are results of reduced consumer spending. Consumer spending also depends greatly on the percent of the population quarantined.

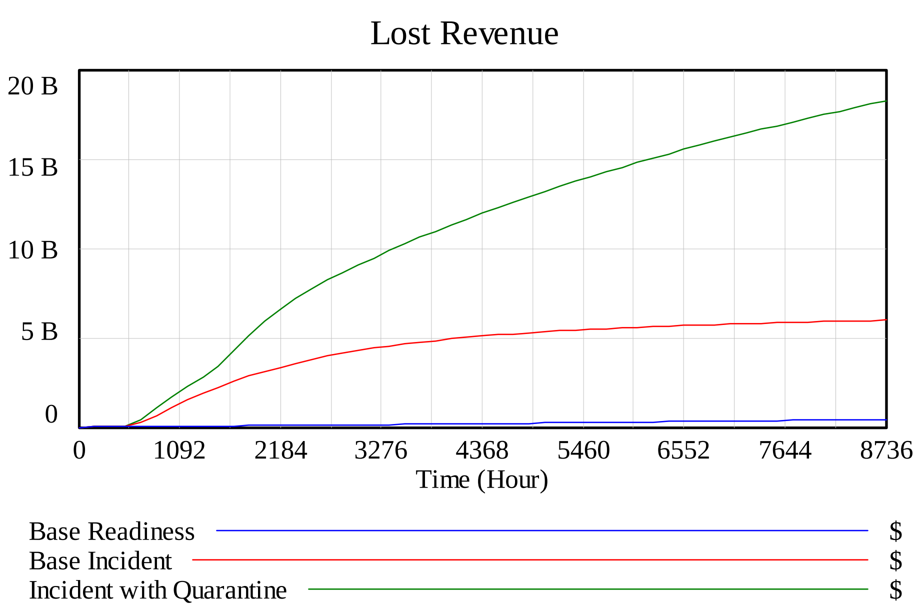

Figure 5. Lost Revenue

[5] Losses are calculated for a period of one year after the beginning of the scenario.

Lost sales, lost wages, and lost value-added are calculated within the economic sector using data from government sources. The data is taken from a real US city and is linearly scaled by population to represent the artificial city used in the simulations. These calculations are performed using the NAICS data for all but the agriculture sector. This method differs from the lost revenue calculation above since lost revenue only represents the critical infrastructure sectors represented in the CIP/DSS model.

Lost sales (see Figure 6) is most directly comparable with the lost revenue calculated above, except, as stated above, lost revenue only represents a portion of the metropolitan economy. In addition, the data source used for sales contains some missing data. Lost wages (see Figure 7) represent a fraction of lost sales, but again this is derived from a data source[6] that contains missing data. While we believe that the numbers are representative, the ratio of these numbers may be biased by the missing data.

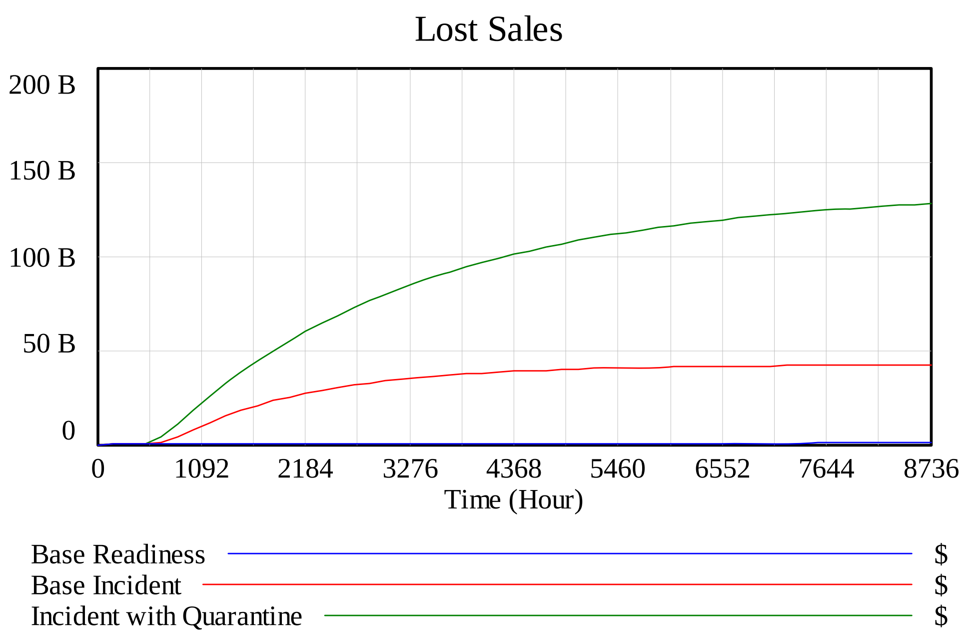

Figure 6. Lost Sales

[6] Data used for the lost wages calculation is from 2003 State and Personal Income from the Bureau of Economic Analysis.

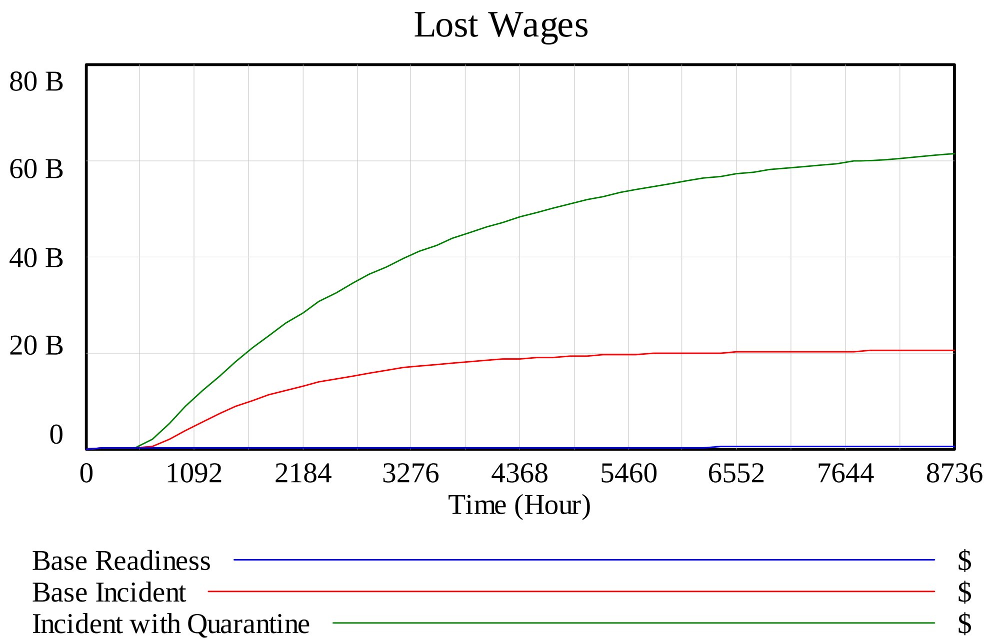

Figure 7. Lost Wages

Although the lost value-added calculations ($55 billion for the quarantine scenario—see Figure 8) are smaller that those of lost sales ($125 billion), they are likely more representative of the loss to the economy from the incident. Gross state product, from which the value-added data is derived, is a portion of the gross domestic product (GDP) of the nation. In this scenario, losses to the metropolitan area are approximately 0.5% of GDP[7]. Perhaps a more important comparison is that losses of $55 billion are less than 10% of the average GSP for the top ten states as ranked by GSP.

[7] Data for GSP and GDP (app. $12 B) are from The Bureau of Economic Analysis.

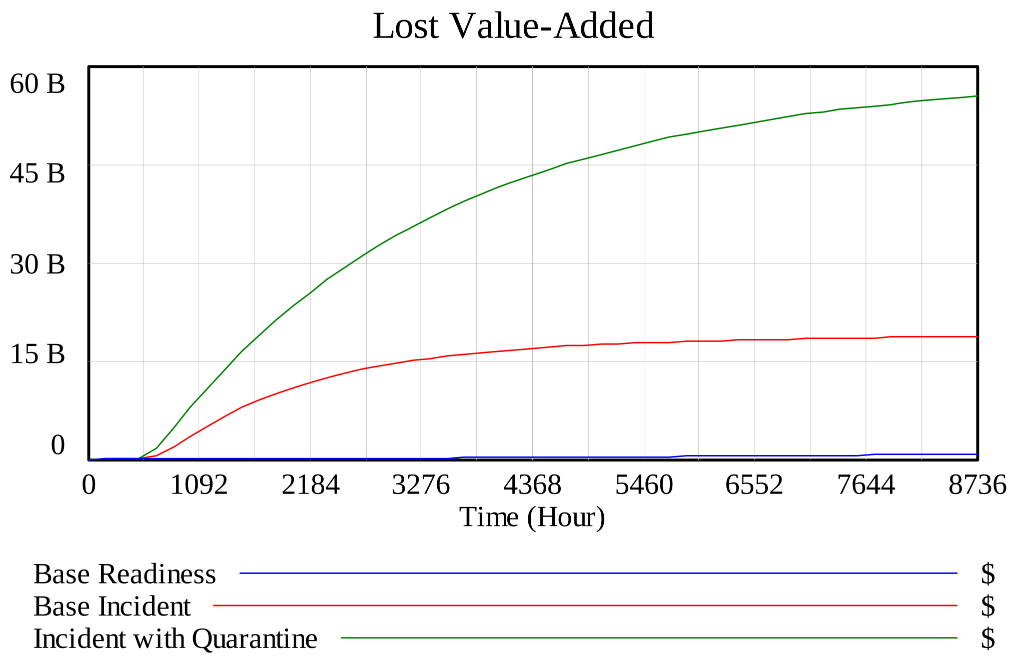

Figure 8. Lost Value Added

Conclusions

Our paper describes a dynamic system for understanding the consequences of various infrastructure disruptions, estimation of the economic effects of those disruptions, and evaluation of the effectiveness of different protective measures. A novel part of our approach is that the disruptions and their economic consequences are modeled as non-equilibrium events, where the interdependent nature of various infrastructures allows event and disruption propagation from one infrastructure to another. This allows us to obtain realistic estimates of economic effects of various disturbances.

In our numeric experiments, we investigate the economic impacts arising from an infectious disease release in the metropolitan area. We also investigate the results of various responses and protective measures. We find that the economic impacts are most significant when the quarantine is imposed. In particular, metrics such as lost sales, lost wages and lost value-added can be on the order of 2-3 times higher than in any other scenario investigated. Those larger impacts mainly arise from the population being prevented from working or spending by the quarantine.

Further research is necessary to better understand the population response to quarantine and to calibrate the model to specific cities. Another intriguing possibility is to enable the model to be run in real-time – where the event data is gathered and imported into the model as the data becomes available. This would allow the decision makers to evaluate and compare different response alternative as the situation unfolds.

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