A SIMULATION FRAMEWORK FOR STUDYING FOREIGN RELIANCE ON REGIONAL SUPPLY CHAINS AT THE INDUSTRY LEVEL

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ABSTRACT

Simulations incorporating economic input/output models have been applied recently to assess the extent of labor shocks from COVID 19 and their impact on supply chains at the macro level. Research is being done to extend these simulations for application to other scenarios of economic shocks beyond what was triggered through COVID related labor reductions. The problem of foreign supply chain dependency is of particular concern to localized regions as a significant portion of their economy is dependent on supplies from overseas. The extended simulation approach proposed here aims to optimize the degree to which the increased inventory supply targets allow for improved economic productivity and the ideal allocation per industry which most efficiently achieves this mitigation. This paper considers the application of the proposed simulation framework to study the regional dependence on the Asian supply chain. The case study presented in this paper demonstrates the economic insight that can be obtained through simulation analysis to support regional government decision making for the state of Alabama.

Keywords: Supply Chain Simulation, Economic Production Modeling, Simulation Optimization.

1 INTRODUCTION

Ensuring supply chain resiliency often involves investments in physical and human capital and may include operational changes that increase the day-to-day costs, such as keeping extra inventory on hand. Such investments or operational changes across the entire supply chain are cost-prohibitive and cumbersome, making it more attractive to focus on the most important links and nodes in the supply chain. The challenge then becomes how to effectively identify the nodes on the supply chain that most impact resiliency. On the regional level, understanding the industries that are most vulnerable to precipitating an economic shock can be even more of a challenge, but is key to protecting against large, regional-level shocks.

Economic shocks are unplanned and unanticipated events that often have widespread and disruptive impacts on an economy (Habermann et al., 2015). Shocks may be caused by changes in technology, firm competition, the environment, patterns of supply and demand, workforce conditions, or the political landscape. This disruption can directly impact any combination of production capacities, supply constraints, demand, transportation, and labor. Because of the mainstream focus of supply chain formation on cost efficiency under normal operations, existing supply chains may be fragile to disruptions (Tang, 2006).

The initial application of the supply chain resiliency modeling framework developed through this research was intended to assess the impact of labor shortages and remote work on regional economic production and how lockdowns can create supply shortages that propagate across industries and regions. An example case study of this application was presented in Hong et al. (2022). The COVID-19 pandemic is one recent example of this type of economic shock. Research on the COVID-19 pandemic and the resulting supply chain disruptions to the global economy has helped identifying additional types and patterns of the propagation of failures across the supply chain. For dramatic disruptions such as COVID-19, researchers and policymakers have found that these shocks affect both supply and demand at every level, and that their impacts create ripple effects across the entire economy (Nikolopoulos et al. 2021; Chen et al. 2021). However, it is persistently difficult for policymakers to evaluate the resiliency regarding disruptions of this scope, especially at state and county levels.

The difficulty in assessing disruptions to supply chains will likely resurface from other types of economic shocks (Kovaks and Sigala, 2021), such as a disconnection of imports and exports from a particular region. Examples of supply chain disconnection include country responses to high tariffs, sanctions, or other reason brought about by political means. This paper presents a new application of the simulation framework focused on supply chain and economic shocks due to foreign import and export disruption. The dependency on Asian nation's supply imports for production in the Alabama region is studied through this modeling framework.

There have been some modeling approaches that have shown promise in quantifying the impact of COVID-19 lockdowns on supply chains globally. Recent modeling efforts by Inoue and Todo (2020) quantified the network effect of a localized COVID-19 lockdown of Tokyo to Japan's national economy through an agent-based simulation approach. The modeling approach used by the authors considered the disruptive impact of the lockdown on supply as well as demand. They concluded that outside of the immediate loss of economic productivity in Tokyo that a lockdown of the city would propagate across the entire country's economy, severely inhibiting national output.

Pichler et al. (2020) developed a more refined economic production model with an input-output basis of the United Kingdom to address the trade-offs between the loss of economic productivity and reducing COVID-19 spread. In this model, the authors quantified the demand shock of consumers in response to the pandemic, and the supply shock created by limitations to on-site labor for certain industries. Most distinctly from previous modeling efforts, this work introduced the utilization of the IHS Market Survey to allow for substitutability of certain inputs. From the policymaking side, these authors considered issues such as the speed of hiring and firing of employees.

This effort looks to extend these modeling approaches to study regional supply chain dependence from one foreign economic region with respect to one region within the United States. This could include a single country, area within a country, or multiple countries. In addition, this modeling framework contains an optimization component to guide the search process with the model for policy related inputs, such as, inventory enhancements to better maximize resiliency. The specific question posed by this research is whether there is enough publicly available data at the industry level to model gross production depletion in a region caused by a cutoff in supply from a foreign supplier. An additional question is whether an optimization algorithm can be used in conjunction with the simulation to locate better inventory policies for a region to reduce this economic shock stemming from a cutoff in supply from a foreign supplier.

2 METHODOLOGY

The modeling framework will be described in this section in addition to the optimization extension used to solve for near optimal resource allocation decisions. Section 3 describes the economic scenario in more detail and how data is regionalized and manipulated to adjust the model inputs for this study. The remainder of the paper provides the results to depict the types of policy decisions that can be supported by this modeling framework as well as the overall capability that this modeling framework provides to better preparing for future economic shocks.

The center of this research is a modeling framework that address on how inventory adjustments and other control variables can mitigate supply chain shortages that may manifest from a variety of economic shocks. Figure 1 is a high-level depiction of the simulation concept model used in this framework.

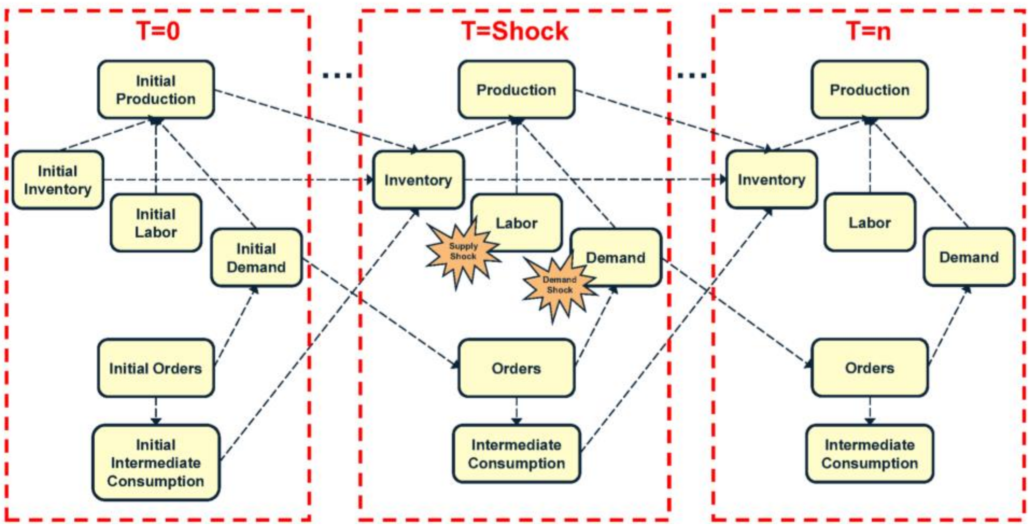

Figure 1: High Level Conceptual Model of the Economic Production Simulation Framework.

The economic production model simulates production at each time step starting at a pre-shock state at time $t = 0$. Total productivity of the economy at each time step is measured in terms of gross output (GO) by the array x_t. Each entry of the array represents one of the 55 major manufacturing and service industries of the US economy. In the first time period the lockdown scenario can initiate producing various shocks to the system's ability to produce outputs. Because the primary source of intermediate inputs to the US economy are sourced domestically, these shocks propagate through the economy, creating shortages in intermediate consumption A_{ij}, where i and j are industries, and gross output x_t. All model components are time-varying with the exception of the recipes matrix A_{ij} which represents the total dollar consumption of inputs from industry i consumed in the production of 1 dollar output for industry j.

In order to describe some of the relationships between the various model variables. We first define the intermediate consumption of input i by sector j at time t, $Z_{i,j,t}$ as,

$$Z_{i,j,t} = O_{i,j,t} \frac{x_{j,t}}{d_{j,t}}$$

$\frac{x_{j,t}}{d_{j,t}}$ is the fraction of the aggregate demand ($d_{j,t}$) for products from sector j at time t that sector j was able to produce at time t ($x_{j,t}$) and consequently $Z_{i,j,t}$, the intermediate consumption, is the fraction of initial orders placed ($O_{i,j,t}$) by sector j for inputs i, that were fulfilled. The inventory update takes the existing inventory of input i for sector j at time t and subtracts the dollar amount of inputs of j used to produce the gross output $x_{j,t}$ which is denoted as $A_{i,j}x_{j,t}$. Then the intermediate consumption of $Z_{i,j,t}$ is added into the inventories. The amount used for production is then removed at that time step.

$$S_{i,j,t+1} = (S_{i,j,t} - A_{i,j}x_{j,t} + Z_{i,j,t})$$

For the model of production, we considered three production functions: linear production, mixed linear-Leontief production, and the Leontief production. Linear production allows for perfect substitution of inputs, whereas Leontief production limits total productivity by the scarcest input. The mixed linear-Leontief production function denotes a subset of the inputs for an industry as essential and allows for substitution of inputs for non-essential inputs.

In summary the simulation model consists of the following input output structure. The inputs consist of the time (days) of the shock event (in this case discontinued supply flow from foreign countries), the length of the shock (days) and the time after the shock (days). The model time step is a day and each of the variables are updated according to the flow equations presented above. In addition to the above equations for inventory, orders and intermediate consumption there are also flow equations for production, demand and labor levels at each time step. There are also parameters that are set by the user to help configure a scenario which are configured before the start of the simulation. These include: τ (speed of inventory adjustment), γ_H (upward labor hiring adjustment), γ_F (downward labor firing adjustment, ρ (consumption adjustment), m (share of labor income used to consume goods), and Δs (change in savings rate). Some nominal values of these variables for perspective are τ = 10, γ_H= 1/30, γ_F= 1/15, ρ = 0.987, m= 0.82, and Δs= 0.5.

The supply chain simulation framework consists of an optimization procedure that involves of inventory levels being the key decision variable along with inventory replenishment rates. The primary objective function is the minimization of the aggregate difference between total economic output during pandemic based on inventory levels. This aggregate difference in total economic output can be expressed as $\min \sum_{t>0,j} \frac{x_{0,j} - x_{t,j}}{x_{0,j}} \Rightarrow \max \sum_{t>0,j} x_{t,j}$ where $x_{t,j}$ is the dollar output of industry j at time t. Inventory dollars to be supplied to sustain production before shocks are constrained and are also added to the model. Here we note c_j is the additional inventory dollars allotted to industry j. A_{ij} is the dollar inputs from i to produce one dollar of j. To operate at pre-pandemic levels, firm j would require $x_{0,j} \sum_i A_{ij}$ total dollar inputs from industries to produce $x_{0,j}$. The new inventory level (in days of production) is $n_j^\star = n_j + \frac{c_j}{x_{0,j} \sum_i A_{ij}}$, with a total constraint on inventory dollars $\sum_j c_j = K$.

A Genetic Algorithm is developed to optimize this economic output depletion during the shock across different combination levels of inventory allocation levels across each industry. This allows the model to be run in an automated manner while searching for the optimal solution. In addition to inventory levels other potential decision variables could include input / output ratios between different geographic areas when transportation time is included into the model.

In application of the Genetic Algorithm, we used a population of size 200 with a crossover probability of 80 percent. We evaluated the logarithm of the objective and placed the stopping condition as the absolute logged differences between generations being less than 0.005 or at a maximum of 10,000 iterations. To verify the solution, we performed 50 independent replications with different random starts comparing overall objectives and distributions of allocations.

3 CASE STUDY

There is significant concern on the dependence of the supply chain from Asian countries for many states and regions in the US. This case study examines the regional impacts in Alabama due to a loss of both imports and exports from China. The proposed simulation framework is applied to study how much of a shock there would be to production if supplies from various Asian countries where cutoff from discontinuing inventory flows between Asian countries and Alabama.
In Alabama, the regional imports from Asian countries affect intermediate consumption and are a supplier to industries that produce a high level of GDP in that area. The dependency of the Asian supply chain varies sector by sector although it is most apparent in the manufacturing sector. This study will measure the effects of GDP depletion over varying lengths of time and will also analyze the effectiveness of any mitigating efforts that involving inventory enhancements.

3.1 Economic Scenario

Alabama's level of imports for each Southeast Asia country are provided in Table 1 below. China is the most notable and accounts for 9.16% of their imports in total. Vietnam is the next largest source for imports and accounts for just under 1% of their total imports. With total imports coming from Southeast Asia accounting for around 12% of their inputs in total it was initially hypothesized that losing trade with these countries would not have a substantial impact on Mobile's economy.

Table 1: Breakdown of Imports by Country to Alabama.

Country	***Alabama***		***United States***	
	Total Imports	**% of World Total**	**Total Imports**	**% of World Total**
Brunei	--	--	$31,874,542	0.001%
Burma	--	--	$92,905,778	0.004%
Cambodia	$2,292,910	0.01%	$2,847,789,619	0.121%
China	$2,037,565,129	9.161%	$468,474,894,856	19.881%
Indonesia	$70,540,741	0.317%	$19,389,820,947	0.822%
Laos	--	--	$32,996,472	0.001%
Malaysia	$78,968,427	0.355%	$30,563,787,818	1.297%
Philippines	$40,977,918	0.184%	$10,189,879,702	0.432%
Singapore	$33,151,096	0.149%	$16,501,526,179	0.700%
Thailand	$59,963,241	0.270%	$27,229,294,785	1.156%
Vietnam	$202,573,817	0.911%	$30,617,650,403	1.300%
World Total	$22,241,800,880	100%	$2,356,356,072,353	100%

As shown in Table 1, the majority of Alabama's imports in 2014 came from countries outside of those identified in the Asia Dependence case study. There is a similar trend when comparing overall US imports from the same countries in Asia. The majority of US imports come from countries outside this area of focus, with the one exception being China – in 2014, almost 20% of US imports came from China.

In 2014 the industries in Alabama with the highest value of imports were Transportation Equipment (336), Oil & Gas (211), Machinery, Except Electrical (333), Chemicals (325), Computer & Electronic Products (334), Fabricated Metal Products, Nesoi (332), Electrical Equipment, Appliances & Components (326), Apparel & Accessories (315), as can be seen in Table 2 below. Transportation Equipment imports were by far the largest commodity imported in 2014. Although not displayed in Figure 2, the pattern demonstrated in Table 1 holds true here as well: the vast majority of these imports came from countries outside of those in the Asia Dependence case study.

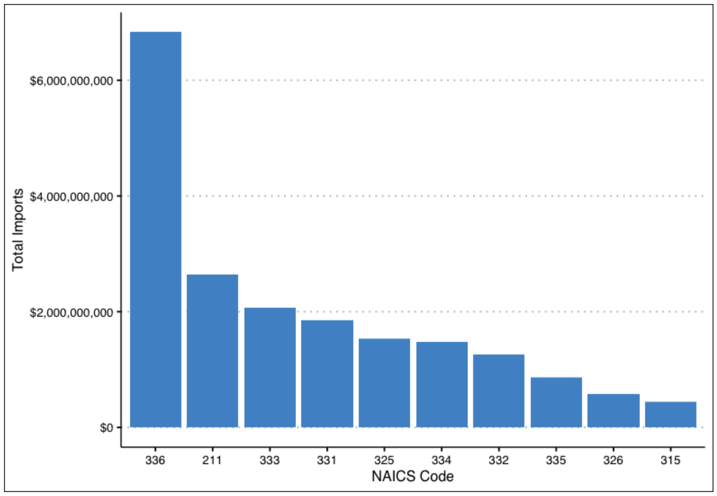

Figure 2: Alabama's Top Imports (by NAICS Code) in 2014.

3.2 Regional Data Aggregation

Because of data availability limitations, one of the more difficult aspects of performing simulation analysis on a regional area are the necessary assumptions and data transformations required to generate an appropriate data set. The primary source of data for this simulation framework is the World Input-Output Database, which provides gross output, intermediate consumption, and final demand data at the national level (Timmer, et al., 2015). Data from the Bureau of Economic Analysis (BEA) SQGDP2 data product on the major private industry groups for state economies was used to obtain regional productivity measures (Bureau of Economic Analysis, n.d.). The BEA SAEXP1 was used to for computing state level demand by differentiating regional differences in regional Personal Consumption Expenditures to national Personal Consumption Expenditures (Bureau of Economic Analysis, n.d.). The magnitudes of the import and export relationships between Alabama and its international partners were estimated using data from the USA Trade Database (United States Census Bureau, n.d.). More discussion on data used to generate the necessary restrictions in supply flow for each country as well as the assumptions used are provided below.

Again, the primary data source for this case study on international trade flow restrictions at the state level comes from the USA Trade Database. This includes dollar value of imports by source, which are of international origin in this case, and destination, which are US states in this case. The data is categorized by NAICS (North America Industry Classification System) codes. For each industry, the proportion of imports imported internationally that is attributed to China and each Southeast Asian country can then be calculated.

We model the dependence on Southeast Asian countries on the state supply chain through the import volumes to the state economy at each time step. Pre-pandemic, the import volume of inputs to the state economy is constant in time. Once the foreign trade shock is activated the volume attributable to various countries is removed from this constant input.

The total import volume to sector j of inputs at time t in dollar inputs from sector i is $I_{i,j,t}$. From the USA-Trade database the proportion of imports from a country k is estimated by $p_{i,j,k}$. To model the removal of imports from this country source, the total imports at each time is defined as,

$$I_{i,j,t} = \begin{cases} I_{i,j} & \text{for } t < t_{\text{shock}} \\ (1 - p_{i,j,k}) I_{i,j} & \text{for } t \geq t_{\text{shock}} \end{cases}$$

Likewise, modeling the shock from the removal of multiple country sources is,

$$p_{i,j,\text{SEAsia}} = p_{i,j,\text{Brunei}} + \cdots + p_{i,j,\text{Vietnam}}$$

4 IMPLEMENTATION OF SIMULATION FRAMEWORK

The specific problem that is being assessed and measured with the simulation framework is the regional impact of reduced trade imports from Southeastern Asian countries. This economic impact is measured in terms of the total gross output for the regional economy during the shock, as well as the time to recovery after the shock has ended.

The region of interest is the state of Alabama and the simulation is run under three different scenarios to investigate the dependency of the state of Alabama's economy on imports from Southeast Asian countries. The first scenario examines the shock to economic productivity stemming from the isolated removal of trade inflows from individual countries in Southeast Asia. The second scenario contrasts the regional dependency of Alabama on Chinese imports against the national dependency of United States as a whole on Chinese imports. The third scenario examines the impact of restricted flow from all countries simultaneously in Southeast Asia while comparing it against the individual removal of inflows from only China.

In the first scenario the shock analyzed pertains to the removal of the flow of imports from the S.E. Asian countries. The level of flow removed from these countries is based on the volume described by the USA Trade data. The simulation results show that the Alabama state economy is able to sustain economic activity throughout the removal of individual inflows from individual countries, with the exception of China & Vietnam. Removing imports from China has the largest impact with over a 3% depletion in regional gross output lasting a year until the recovery period. This impact is related to industries which have critical a critical need for supplies in Oil & Gas, Machinery, Chemicals, Fabricated Metal Products, and Electrical Equipment.

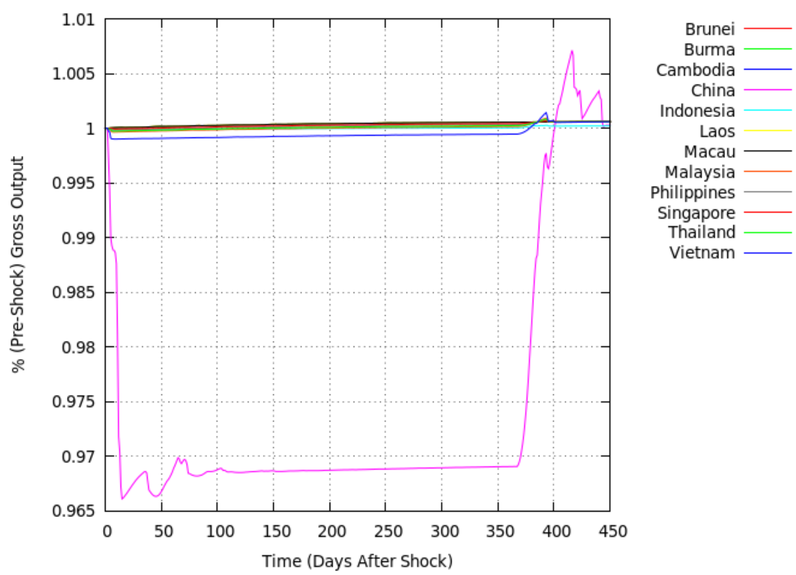

Figure 3: Economic Production Reduction due to a Shock from Each Country.

In the second scenario, we compare the shock induced in the USA overall versus what would be triggered in Alabama due to a cutoff in supplies from China over a one-year period. The simulation is run from the regional Alabama model against the national level model which is also included in the framework (Hong et al., 2022). The results show that the expected daily output from the US to decline by a little less than

2%, but for Alabama's state economy to decline by a little more than 3%. This reduced daily output would accumulate up to $3.859T over the course of a year or on average $10.572B per day. These simulation results suggest that Alabama has a slightly stronger dependence on Chinese imports than the US at large and would be more adversely affected. However, the observed shock of removing Chinese imports resulted in a slightly over 3% drop in GDP and suggested a rapid recovery in response to resumed trading. These results were consistent across the multiple production functions that were considered.

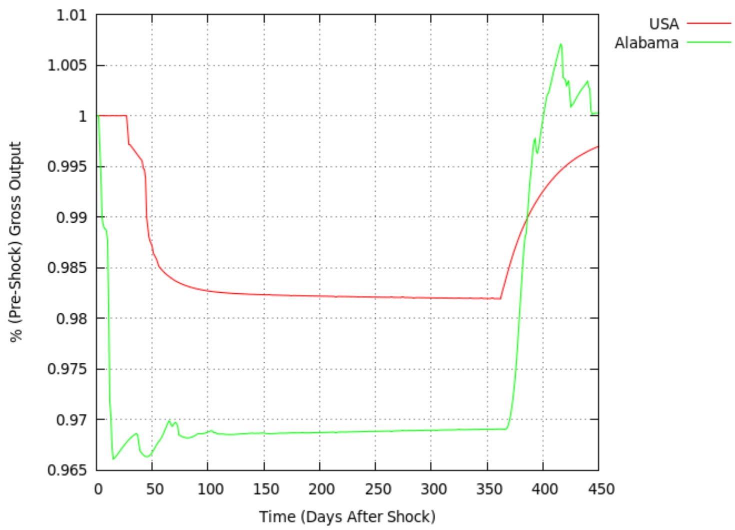

Figure 4: Alabama's China Dependency vs. The United States.

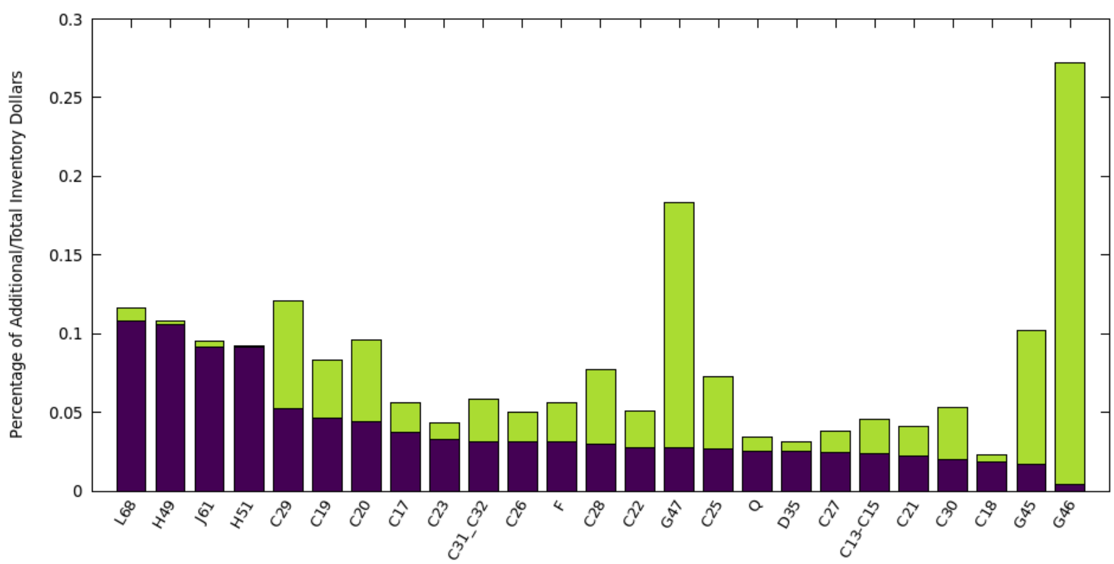

Figure 5: Optimized Inventory Increments for each Industry.

For increasing inventories to buffer against the loss of Chinese imports, we perform genetic search over the simulation model, allowing for additional $1B inventories to be spread across the major industries in the region. As shown in Figure 5 below (with industries depicted in the x axis), the search suggests increasing inventories in the sectors: L68 (Real Estate), H49 (Land Transportation), J61 (Telecommunications), H51 (Air Transportation), & C29 (Manuf. Motor Vehicles), would best lessen the impact of this shock to Alabama's economic output.

In the final scenario, we compare the removal of all inflow of trade volume from Southeast Asia versus removing only inflow from China. This allows for comparing the dependency on China versus the dependency on Southeast Asia as a whole. The results of the simulation framework suggest that the economic productivity for Alabama persists above 70% for around 350 days until inventory depletion. The shock caused by removal of inflow from China is not significant when compared to the gross output reduction caused by the removal of supplies from all of Southeast Asia. In the all of Southeast Asia scenario, the gross output for Alabama falls by over 90%. These results also suggest that economic productivity continues to decline after resuming import activity as inventories are completely depleted.

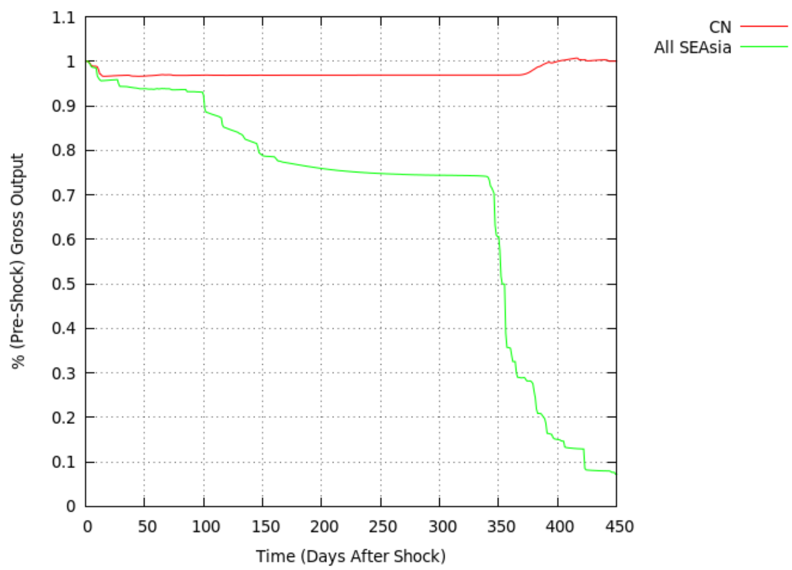

Figure 6: Predicted Shock from Removal of All Asian Countries.

5 DISCUSSION

This case study with the proposed simulation framework demonstrates how our supply chain modeling capability can be extended past labor reduction shocks to quantify the impact of other disruptions. These disruptions could also include the implementation of new policies or initiatives. For example, a region may leverage the framework to determine the effects of using federal funds in regional development projects due to the "Buy American" provisions of the American Recovery and Reinvestment Act which requires iron, steel, and manufactured goods to be procured from American suppliers (2 C.F.R. Part 176, Subpart B.). The model would be useful in understanding how supply levels may change due to shifts in supply source. It could also be applied to forecast the effects of a shock under varied import-share scenarios.

Decision makers may also wish to understand the potential effects associated with regional economic development initiatives that provide technology grants and workforce incentives to build a regional presence of an industry, new tariffs on a product or supplier category, or implementation of a new procurement policy requiring a minimum recycled content. This simulation framework can be applied to study how these potential shifts in supply flow can effect gross output in a regional level. Moreover, the simulation outputs in this paper showed gross output across all 55 industries combined. The simulation can also provide outputs with respect to specific industries to examine industries that are believed to be more sensitive to a shock. In addition, it can output inventory levels by industry to help diagnose where the biggest bottlenecks are.

6 CONCLUSION

This paper provides an introduction to a new simulation framework that is being applied to study regional supply chain resiliency. The framework is being extended to study a variety of potential economic shocks ranging from supplier dependence, labor shortages, and transportation delays. This paper focused on the application of the framework to study regional dependence on countries or regions outside of the United States. The case study focused on examining the capability of the proposed simulation framework in measuring supply chain dependency regarding the state of Alabama and the US with respect to Southeast Asia.

This case study showed the simulation and optimization framework has the capability to identify a region's vulnerability from reduced imports from an external region. From the case study the simulation framework showed that Alabama's state economy would decline by a little more than 3% when discontinuing supplies from China, which would reach up to an average of $10.572B per day towards the end of the year. The simulation framework was able to show that the observed shock of removing Chinese imports resulted in a rapid recovery in response to resumed trading. Moreover, the simulation optimization procedure was able to locate critical industries, which included L68 (Real Estate), H49 (Land Transportation), where additional inventory allocation would significantly lessen the shock. The simulation framework also has the capability to generate the above results on an industry-by-industry basis although these figures are not presented in this paper.

Future work will entail additional leveraging of the inventory optimization procedure discussed in Section 2.2 to solve for additional inventory enhancements that minimize the reduction in gross output for Alabama and the US under a shock related to reduced supplies from Southeast Asia. Extensions are also being performed from a modeling methodology perspective to enable the study of shocks from transportation issues which result in delays in moving supplies from one region to another.

ACKNOWLEDGMENTS

The authors would like to acknowledge Bridgette Clark of the MITRE corporation for helping bridge this research towards government policy decisions and David Rodgers of the Mobile Area Chamber of Commerce in Mobile, Alabama for helpful feedback on the model decision recommendations and feedback on design factors towards the simulation framework.

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