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Transportation Infrastructure Readiness for Post-Pandemic Supply Chain Transformation for Greater Resilience: Part 2 - Readiness & Resilience

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16. Abstract

This project evaluated United States transportation infrastructure readiness for supply chain reshoring in critical products. It asked, "Can our civil infrastructure support U.S.-based production increase from reshoring should we bring manufacturing back to the U.S.?" To support this study, a quantitative evaluation framework with impact analysis, national resilience evaluation, and tradeoffs assessment modules was developed to estimate and tradeoff infrastructure and environmental impacts against national resilience and economic improvements resulting from reshoring. Findings from application of the framework on a scenario involving reshoring of N95 filtering facepiece respirators and microchips were obtained. Readiness for large-scale reshoring in a much broader array of industrial sectors was also evaluated. Results indicate potentially significant benefits from reshoring in terms of national resilience and other economic metrics. Moreover, it also found that the existing U.S. transportation infrastructure should be sufficient to support large-scale reshoring efforts, but at significant costs to some locations.

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CHAPTER 1

Introduction

BACKGROUND

Motivated by tax incentives and low labor costs available abroad, businesses with headquarters in the United States and other developed nations have moved their manufacturing operations overseas (Ellram et al., 2013; Zhai et al., 2016). However, in recent years, there has been a call to bring manufacturing home, especially in the United States, but also in such nations as the United Kingdom (Bailey and De Propris, 2014) and Germany (Kinkel, 2014). In the United States, this call for reshoring (or "revitalization in American manufacturing" (The White House, 2022) has come from both the government and organizations that represent domestic workers (Sirkin et al., 2012; U.S. Congress, 2020). The Boston Consulting Group estimated that reshoring of seven industries from China (computers and electronics, appliances and electrical equipment, machinery, furniture, fabricated metals, plastics and rubber and transportation goods), combined with increased exports due to improved U.S. competitiveness, could create 2 to 3 million U.S.-based jobs and add $20 to $55 billion annually to the U.S. economy (Sirkin et al., 2012). In fact, a cumulative 1.6 million jobs were estimated to have been created between 2010 and 2022 from moving manufacturing to the United States by both U.S. (e.g., General Electric and Ford) and foreign companies (Moser and Kelley, 2022).

Reshoring the supply chains (SCs) of critical products can aid in not only improving domestic economic well-being, but also increasing national security. Numerous nations have faced the consequences of allowing overseas production of their most critical supplies, many of which quickly became inaccessible as a consequence of SC disruptions and international impedances (e.g., personal protective equipment (PPE), hand sanitizer, paper goods, and meat) arising at the onset of the COVID-19 pandemic (Engstrom et al., 2021; Moore, 2021). National security concerns arising from outsourcing has been recognized in many industries, including agri-food (Ali et al., 2022), pharmaceutical (Gurvich and Hussain, 2020), and semiconductor industries (Lieberman, 2003; Harada, 2010). Moreover, less reliable supplies of these key products can lead to further disruptions to SCs of products that rely on them. Consider, for example, the impact of a microchip shortage on the production of computers, mobile phones, and even defense systems (Gould, 2022).

The costs of reshoring are nontrivial. In addition to direct costs of recreating operations in a new location with a new labor force, there are broader national and international costs to companies and for the U.S. government for bringing manufacturing home. Capri (2020) conjectured that a self-sufficient economy achieved by what he called "techno nationalist policies" and reshoring could erode significant gains in international trade. Others note a likely increase in cost of the end products and potential for inflation as a result of shifting offshore manufacturing back to the United States (Evstatieva, 2021).

There are additional costs of reshoring that have received less attention, including the cost to the U.S. infrastructure. Transportation infrastructure systems, in particular, form the backbone of worldwide SCs. Internally, road, rail, and air networks play a crucial role in the movement of raw materials to processing plants, middle products between factories or between factories and warehouses, and end products to distribution points and, finally, consumers. Whether this infrastructure can support large reshoring efforts requires examination. This research investigates the viability of restructuring SCs toward bringing the manufacturing and production of middle- and end-products critical to national security home. It asks the question, "Can our civil infrastructure support this U.S.-based production increase from reshoring should we bring manufacturing back to the U.S.?" The research further assesses the value of reshoring toward increasing national resilience (a contributor to improved national security), and investigates the U.S. transportation system's readiness for a SC transformation from large-scale reshoring.

A review of the literature on the impact of SC reshoring and its implications for transportation infrastructure and national resilience was conducted, results of which are provided next. This review indicates significant gaps in our understanding of how SC reshoring could strain existing transportation systems and its potential for increasing national resilience. Chapter 3 presents a framework for assessing the impacts from reshoring the manufacturing of one or more key products and restructuring their SCs accordingly. The framework estimates the negative impacts of reshoring relevant to the transportation infrastructure and environment, proposes a measurable metric of resulting national resilience improvement, and suggests consideration of tradeoffs between the negative impacts and potential gains in national resilience improvement, GDP and the domestic job market. The presentation of the framework is followed by outcomes from its implementation in studying the impacts of a reshoring scenario involving N95 filtering facepiece respirators (FFRs) and microchips in Chapter 4. Tradeoffs between added total truck-miles (TMs) and truckloads (TLs), roadway maintenance costs, fuel consumption, emissions, and potential truck-related incidents versus the benefits of avoided economic losses (used in creating a surrogate for national resilience herein), increases in GDP, added jobs, and excess production capacity are considered. Chapter 4 expands on these findings to comment on U.S. readiness for large-scale SC reshoring to support increased domestic production of a larger set of critical goods and improved national resilience. Last, limitations of the study and potential extensions are discussed in Chapter 5.

OBJECTIVES

This project evaluated U.S. transportation infrastructure readiness for SC reshoring in critical products from across a broad range of industries. It asked, "Can our civil infrastructure support U.S.-based production increase from reshoring should we bring manufacturing back to the U.S.?" Through quantitative analyses, it traded off transportation infrastructure and environmental impacts against potential gains in national resilience and other economic indicators.

DATA AND DATA STRUCTURES

The framework was illustrated on a scenario comprised of reshoring goals for two SCs supporting the manufacturing of products in differing industries, specifically N95 FFRs from the surgical appliance and supplies manufacturing industry and microchips from the semiconductor and related device manufacturing, following the North American Industry Classification System (NAICS) conventions (Executive Office of the President Office of Management and Budget, 2017).The N95 FFR has shown its crucial role in the fight against the COVID-19 pandemic (USCDC, 2020), and government agencies facilitated considerable reshoring of this product accordingly (USDOD, 2020). Microchips are ubiquitous and have proven to be almost as critical, with recent shortages leading to shortages in a wide variety of products, ranging from vehicles (Moore, 2021) to refrigerators (Leprince-Ringuet, 2021). As such, government agencies have offered incentives (e.g., short-term tax credit for N95 FFR manufacturing (NJEDA, 2021)) and long-term property tax breaks (Sohn, 2021), for microchip manufacturing to enable reshoring or bolster American production of these important products. Estimates are taken over a 2-year period assumed to occur after SC restructuring and/or production capacity changes are complete.

In the N95 FFR SC, 26 crude oil suppliers, 48 imported N95 FFR suppliers, 19 oil refineries, 3 polypropylene resin plants, 7 meltblown polypropylene nonwoven fabric plants, 6 spunbond polypropylene nonwoven fabric plants, 7 N95 FFR plants, and 48 distributors are modeled as candidate entities, with 4,365 hospitals modeled as the end customers. In the microchip SC, 48 raw wafer suppliers, 72 chemical plants, 4 distributors, and 20 fabs are modeled as candidate entities, with 4 assembling, testing, and packaging (ATP) plants modeled as end customers. The 20 fabs included 15 existing fabs and 5 potential locations for new fabs that were broadly mentioned in news outlets at the time of modeling (Shilov, 2020; Sohn, 2021). These 5 include Goodyear, Arizona; Phoenix, Arizona; Queens Creek, Arizona; Genesee, New York; and Taylor, Texas.

CHAPTER 2

Literature Review

Numerous works have studied the driving forces behind reshoring (Gray et al., 2013; Ellram et al., 2013; Tate et al., 2014; Foerstl et al., 2016; Fratocchi et al., 2016; Wiesmann et al., 2017; Cohen et al., 2018 and Orzes and Sarkis, 2019). Ellram et al. (2013) suggested eight factors, including physical character of input/product, cost, labor, logistics, SC interruption risk, strategic access to market and knowledge, country risk and finally, government trade policies, that affect a company's decision to manufacture their products offshore or to return to domestic production. Based on 139 cases for reshoring of American manufacturing companies with plants in China, Zhai et al. (2016) found that quality, instead of the rising labor cost, is the primary factor supporting reshoring decisions. In a comprehensive review, Fratocchi et al. (2016) presented an interpretative framework that includes 31 motivating factors for reshoring, indicating the complex nature of reshoring decisions. Wiesmann et al. (2017) categorized the drivers of and barriers to reshoring according to their sources, such as access to raw materials, supplies and markets, and politics. Sustainability is an additional motivating factor for reshoring (Wiesmann et al., 2017; Orzes and Sarkis, 2019).

A few works have looked at the potential detriments for companies pursuing reshoring. Gray et al. (2013) asserts that reshoring could lead to long-term losses, as the growth potential for markets in developing countries is significant and locating nearer to future markets has important benefits. Shih (2014) used the MotoX mobile phone SC as an example to show that if only final assembly and manufacturing of a subset of the components are reshored, few benefits would be gained unless new, home-based suppliers of the remaining parts can be identified. Additionally, the logistical costs from importing those components not obtainable locally could outweigh any gains. Moreover, van Hoek and Dobrzykowski (2021) noted that for some products, price increases incurred from reshoring would likely lead to demand reduction.

While numerous works have studied various aspects of reshoring, few works have investigated whether the U.S. infrastructure can support large-scale reshoring. Some works that quantify the impacts of reshoring on local freight transport demand may be relevant. Using historical freight analysis framework (FAF) data, Sarder et al. (2016) predicted the potential increases in flows of domestic freight volumes within the U.S. and concurrent decreases in freight volumes at major U.S. ports for several scenarios. They estimate inland regional flows and imported commodity flows from ports. They do not model SC logistical or production decisions.

Another relevant set of works studied the impacts of production expansion of specific commodities on local roadways (Bai et al., 2010; Hajibabai et al., 2014; Fried et al., 2018; Chen et al., in review; Miller-Hooks et al., 2022). Chen et al. (in review) and Miller-Hooks et al. (2022) proposed an analytical framework with embedded mathematical methods for assessing the impacts of SC restructuring and domestic capacity expansion on a nation's roadways. Their work uses a similar optimization-based methodology as in (Ottemöller and Friedrich, 2019; Nicholson et al., 2011; Atallah et al., 2014) for approximating SC structure.

Numerous works have focused on building resilient SCs (e.g., Christopher and Peck, 2004; Ponomarov and Holcomb, 2009; Hohenstein et al., 2015; Kamalahmadi and Parast, 2016; Doroudi et al., 2018; Hosseini et al., 2019; Narassima et al., 2022). These studies consider resilience primarily in terms of continuity of business post-disruption. Another important area of focus has been on SC risk management, more specifically risk identification and disruption mitigation. Reviews of the literature on this topic can be found in (e.g., Jüttner et al., 2003; Tang, 2005; Tomlin, 2006; Kleindorfer and Saad, 2009; Tang and Nurmaya Musa, 2011; Ho et al., 2015). The necessity of a functioning transportation system as key to maintaining a resilient SC is also widely acknowledged (e.g., Christopher and Peck, 2004; Wilson, 2007; Tang and Nurmaya Musa, 2011; Meyer et al., 2019).

The role of resilient SCs in regional, national, or global resilience has received less attention in the academic literature, and whether reshoring will improve or reduce national resilience is still a controversial topic. Several works (e.g., Gurvich and Hussain, 2020; Keelan et al., 2021) call for reshoring of pharmaceuticals and other healthcare products for the purpose of improving national resilience. Contrary to this call for reshoring, Lincicome (2021) suggests that such reshoring could undermine national security and global integration could bolster national security. Lincicome (2021) used historical data from steel, shipbuilding, semiconductor, and machine tool industries to support these arguments.

Fjäder (2014) noted a lack of definition of national resilience and suggested consideration of national security, civil emergency management and critical infrastructure protection as contributing measures to national resilience. The larger transportation system's role in maintaining national resilience is discussed in (Chacon-Hurtado et al., 2020). In an analysis of the relationship between the economy and national security, Retter et al. (2020) identified supplier dependence as one of seven key factors that, through their potential for economic impact, create a threat to national security. The other six factors are: ownership (through control and influence) by public or private actors of critical infrastructure and sectors, espionage and access to sensitive information, natural resource dependence, government intervention, corruption and fraud, and socio-economic inequality. While focused on community resilience, a notion of resilience based on the ability to avoid economic loss proposed in (Rose, 2007) also has relevance where critical products are involved, contributing to national resilience as suggested in Chapter 3, as well as security.

It appears that no prior work has studied the potential impacts of large-scale reshoring on a nation's infrastructure, nor has any prior work developed techniques for understanding the impact of reshoring on a nation's resilience. In fact, whether reshoring will improve national resilience is not fully understood. This research sought to fill this gap. The evaluation framework is applied on a case study with two products (N95 FFRs and microchips). The readiness of the U.S. roadway infrastructure to absorb the added truck traffic and its consequences from large-scale reshoring scenarios was also evaluated.

CHAPTER 3

Methodology

INTRODUCTION

The proposed evaluation framework for investigating transportation infrastructure readiness for major SC transformation in support of large-scale reshoring ventures and its potential for creating greater national resilience is presented next. The framework considers positive (e.g., increased production capacity, economic well-being (GDP and job opportunities), improved national resilience) and negative (e.g., increased roadway congestion, maintenance costs, fuel consumption, emissions, and hazmat incidents) effects of reshoring, and considers their tradeoffs to provide insights into both the burden and corresponding resilience gains from reshoring.

An overview of the evaluation framework is presented in Figure 1. The framework is comprised of three key modules: (1) the Supply Chain Restructuring and production growth Impact analysis (SC-RI) (adapted from Chen et al., in review and Miller-Hooks et al., 2022) module for estimating the impacts of reshoring on the roadway network; (2) National Resilience Evaluation (NRE) module for evaluating the improvement in national resilience, measured as a function of percentage of avoided economic loss; and (3) Impact and Resilience Tradeoff Evaluation (IRTE) for conducting a tradeoff analysis to assess the gains in national resilience along with other positive effects against the corresponding negative impacts on the national infrastructure and environment. Separate from the evaluation framework, a Scaling of National Impacts for Large-scale Reshoring Scenarios (SNI) technique is suggested for estimating impacts from much larger-scale reshoring scenarios. The SNI method is used in assessing national readiness for large-scale reshoring. The following subsections provide the details of these key modules.

SUPPLY CHAIN RESTRUCTURING AND PRODUCTION GROWTH IMPACT ANALYSIS MODULE (SC-RI)

The SC-RI module enables the analysis of the impacts that result from changes in transportation requirements created from SC restructuring and/or increased production of a given product. The analysis is repeated over all SCs contained in the considered reshoring scenario and their impacts are summed. The module is comprised of three major submodules: (1) SC-profiling, (2) SC-structure and commodity flow analysis, and (3) SC-impact analysis. The inputs of this module include the location of facilities, transportation channels, supply- and demand-side attributes, production and transportation cost parameters, and bill of materials.

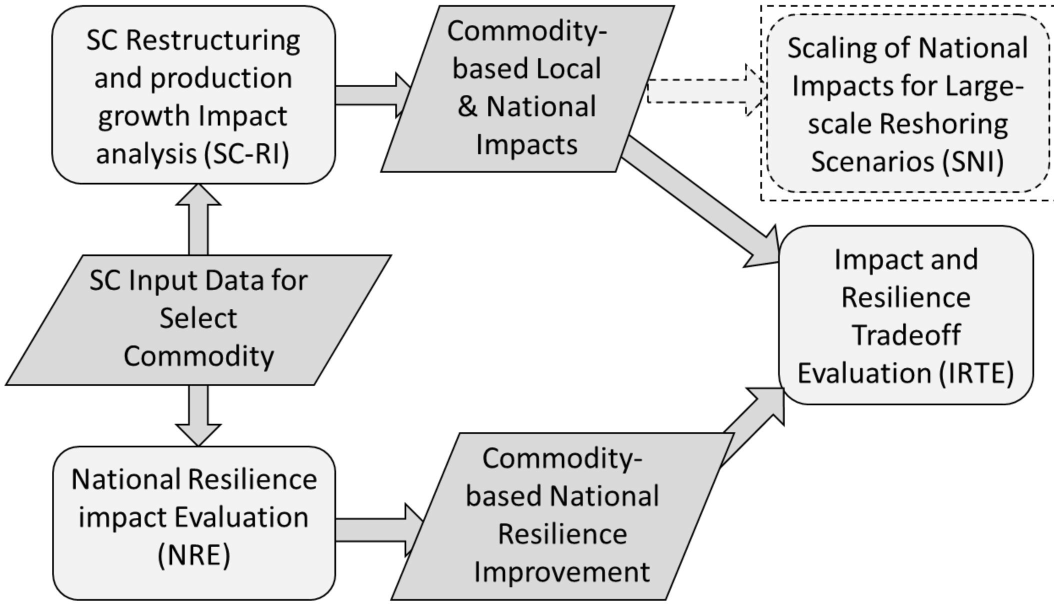

Figure 1. National readiness and resilience SC reshoring evaluation framework.

In the SC-profiling submodule, information about existing and potential entities, transportation channels, supply and demand attributes, parameters for cost estimation, and bill of materials are collected and processed. The SC as it exists currently and the SC as restructured or expanded for production growth, along with related commodity flows through the SC, if not known, are approximated through solution of a pair of mathematical models in the SC-structure and commodity flow analysis submodule. The outcomes of this submodule are given in terms of added TLs and TMs. The SC-impact analysis submodule gives an evaluation of secondary impacts, including traffic congestion given by a speed reduction index (SRI) (Afrin and Yodo, 2020), roadway maintenance costs, domestic fuel consumption, emissions from GHG and other air pollutants, and truck-related incidents and incidents involving trucks carrying hazardous materials that result from the SC modifications. Impacts of a chosen reshoring scenario are evaluated at both local and national levels. Details of the SC-RI methodology can be found in (Chen et al., in review and Miller-Hooks et al, 2022).

NATIONAL RESILIENCE IMPACT EVALUATION (NRE)

Reshoring contributes to resilience through two key mechanisms: (1) increasing domestic production capacity, and thus, increasing the inherent coping capacity by producing more critical products in advance; and (2) availability of at-the-ready production capability and capacity (adaptability) for domestic production of commodities when critically needed.

To assess the national resilience improvement from increased domestic production from SC reshoring, a concept of regional- or community-based economic resilience computed in terms of percentage of avoided economic loss as described in (Rose, 2007; Dormady et al., 2022) was proposed.

Let c_i be the lost market value for commodity i that arises when demand for commodity i cannot be fulfilled due to insufficient supply, d_i be the demand for commodity i, s_i be the available supply of commodity i, and $f_i(\cdot)$ be the unit price of commodity i; c_i is computed by equation (1).

$$c_i = \begin{cases} \sum_{x=1}^{d_i - s_i} f(x) & if\ d_i > s_i. \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

The lost market value (i.e., c_i) can be interpreted as the additional income that could have been attained if additional supply of commodity i were to exist that could satisfy all demand. With increased domestic production capacity to provide additional supply g_i, the loss can be reduced to c'_i, defined in equation (2).

$$c'_i = \begin{cases} \sum_{x=1}^{d_i - s_i - g_i} f(x) & if\ d_i > s_i + g_i. \\ 0 & \text{otherwise.} \end{cases} \quad (2)$$

The avoided economic losses, Δc_i, resulting from increased domestic production of commodity i by quantity g_i, used in support of the domestic market, can be computed as in equation (3).

$$\Delta c_i = c_i - c'_i = \begin{cases} \sum_{x=d_i - s_i - g_i}^{d_i - s_i} f(x) & if\ d_i > s_i + g_i \\ \sum_{x=1}^{d_i - s_i} f(x) & if\ s_i \leq d_i \leq s_i + g_i \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

The ratio of avoided potential losses is used to measure resilience improvement, which is calculated as in equation (4).

$$R_i = \Delta c_i / c_i. \quad (4)$$

Given that $f(x)$ is positive, under a positive unfulfilled demand, $\sum_{x=d_i - s_i - g_i}^{d_i - s_i} f(x) > 0$ when $d_i > s_i + g_i$, and $\sum_{x=1}^{d_i - s_i} f(x) > 0$ when $d_i > s_i$. Also, $\Delta c_i > 0$ if $g_i > 0$. Thus, $0 \leq R_i \leq 1$. $R_i = 1$ infers that all economic loss is avoided and the maximum resilience is obtained, while $R_i = 0$ infers that no resilience improvement is created. According to equations (3) and (4), R_i is an increasing function of additional domestic supply g_i that reduces the unfulfilled demand when $g_i < d_i - s_i$.

There are several mechanisms related to SC reshoring through which the unfulfilled demand can be reduced, thus enhancing national resilience. These mechanisms broadly involve: (a) supplier management via, for example, substitutions and temporary production capacity increase through increases in work shifts; (b) influencing customer behavior through increased consumer confidence in product availability, and thus, reduced benefits of panic stocking or hoarding; (c) reducing monopolistic behavior through increased domestic participation in the production SC (Munson and Rosenblatt, 1999) and increasing equity in product distribution; and (d) enhancing government control by providing more options to award government contracts to domestic producers that support the SC.

Equation (4) can be used to quantify the economic resilience improvement from reshoring as a consequence of reshoring initiatives, whether the initiatives target supply-, demand-, or market-side goals. The equation can also be expanded to incorporate second- and third-level (indirect) impacts, such as losses from decreased availability of personnel due to, for example, lack of PPE, or non-economic impacts, such as fatalities.

IMPACT AND RESILIENCE TRADEOFF EVALUATION (IRTE)

In this module, the positive effects of increased national resilience, avoided economic losses, increased domestic jobs, and other benefits of reshoring are compared against the incurred negative impacts associated with increased domestic production and supply chain reconfiguration at both national and local levels.

For a commodity i, the negative impacts depend on the total domestic production, g_i. Let $P_i(g_i)$ be the negative impacts of producing g_i units of product i. $P_i(g_i)$ is an increasing function with respect to production level g_i that is either linear or diminishes with increased production level. It is shown by a dashed line in Figure 2. Given an unfulfilled demand, $w_i = d_i - s_i$, national resilience improvement created by reshoring the manufacturing of commodity i is also an increasing function of g_i in a portion of its range. That is, the greater the demand gap that is filled, the greater the resilience improvement. As such, R_i can be given as $R_i(g_i)$ and shown through the solid line in Figure 2. It is shown with concave shape to capture the higher unit cost associated with greater unfulfilled demand w_i for critical commodities. Through monetary or other conversion methods, $P_i(g_i)$) and $R_i(g_i)$ can be made comparable. Doing so, their relationship via g_i can be illustrated as in Figure 2.

If the unfulfilled demand for a commodity i is large enough, then there exists a balance point (g_i^e) at which the negative impacts from increased domestic production are equivalent to the gains in national resilience improvement. A commodity i is worth reshoring if $w_i \geq g_i^e$, and the best reshoring strategy is to reshore as much as possible up to the point that the demand is fulfilled. Moreover, a minimum of g_i^e should be reshored; otherwise, the negative impacts would outweigh the benefits to national resilience, i.e., $P_i(g_i) > R_i(g_i)$. If $w_i < g_i^e$, then the added resilience will not be justified given the impacts from the fixed costs of initiating the reshoring effort (i.e., P_i^{min} in Figure 2). Thus, reshoring of this commodity would not be justifiable.

By equation (3), when the unfulfilled demand is reduced to zero through increased domestic production, any additional increase in production will not increase resilience, i.e. a maximum resilience level, R_i^{max}, is met (the right side of vertical line $g_i = w_i$ in Figure 2), and $g_i = \max\{d_i - s_i, 0\}$ is the maximum suitable reshoring amount.

The shapes of the resilience improvement (solid line in Figure 2) and impact (dashed line in Figure 2) curves are determined by SC characteristics (e.g., criticality of the final commodity to the market, raw material volume to final product volume ratio, and transportation distances between plants), while the unfulfilled demand (w_i) is exogenously determined by the market. Both play an important role in determining whether the positive gains from reshoring will outweigh the negative impacts. Generally, a product with less negative impact potential (having a small initial setup impact (P_i^{min} in Figure 2) and flat or diminishing impact curve), greater unfulfilled demand (with $w_i \geq g_i^e$), and significant criticality with increasing value as a function of the unfulfilled demand will have priority for reshoring.

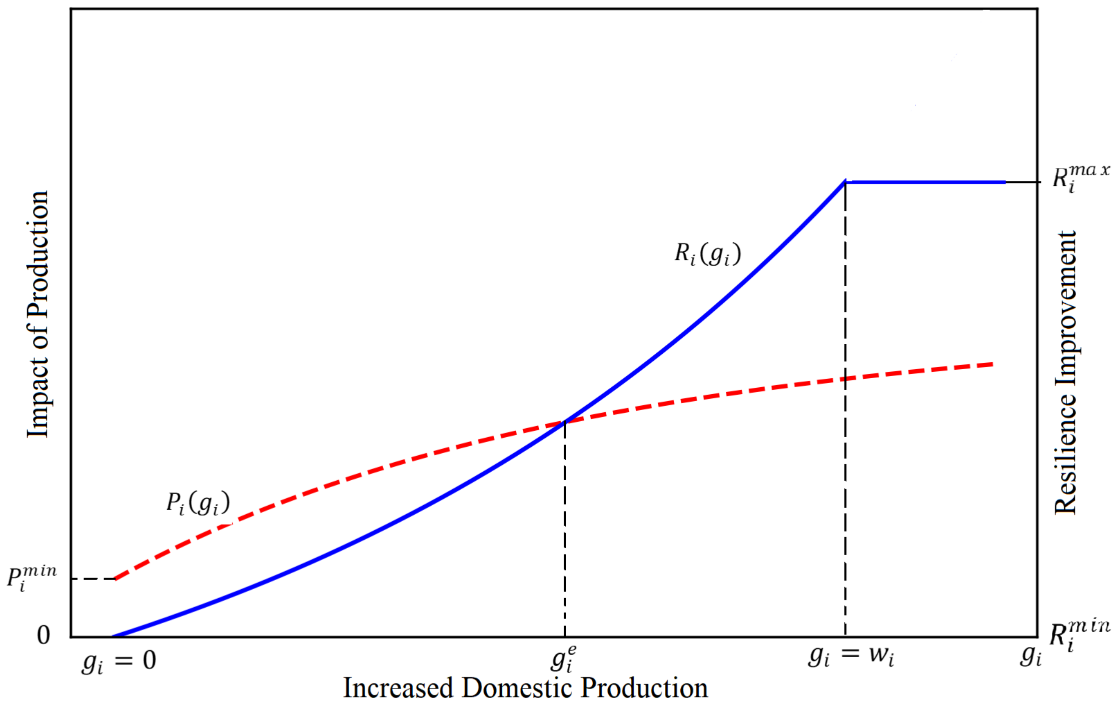

Figure 2. Impact and resilience improvement with increased domestic production.

CHAPTER 4

Application and Findings

APPLICATION AND EXPERIMENTAL DESIGN

The framework was illustrated on a scenario comprised of reshoring goals for two SCs supporting the manufacturing of products in differing industries, specifically N95 FFRs from the surgical appliance and supplies manufacturing industry and microchips from the semiconductor and related device manufacturing, following the North American Industry Classification System (NAICS) conventions (Executive Office of the President Office of Management and Budget, 2017).The N95 FFR has shown its crucial role in the fight against the COVID-19 pandemic (USCDC, 2020), and government agencies facilitated considerable reshoring of this product accordingly (USDOD, 2020). Microchips are ubiquitous and have proven to be almost as critical, with recent shortages leading to shortages in a wide variety of products, ranging from vehicles (Moore, 2021) to refrigerators (Leprince-Ringuet, 2021). As such, government agencies have offered incentives (e.g., short-term tax credit for N95 FFR manufacturing (NJEDA, 2021)) and long-term property tax breaks (Sohn, 2021) for microchip manufacturing to enable reshoring or bolster American production of these important products. Estimates are taken over a 2-year period assumed to occur after SC restructuring and/or production capacity changes are complete.

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FINDINGS

Local and National Impact Analysis through the SC-RI Module

Local-level impacts

The impact at the local level is identified (Table 1). For the N95 FFR SC, with an increase of 3,470 TLs (from 1,112 to 4,582) over the 2-year study period, the maximum TL increase is found on the route between the crude oil port in Houston and the refinery plant in Houston. The additional TLs (equivalent to approximately 1 truck per hour) have trivial impact on traffic congestion for roads connecting these two locations. The maximum TM increase is found on the route between the N95

FFR plant of Honeywell at Smithfield, Rhode Island and the distributor at Columbus, with an increase of 470,000 TMs over the 2-year study period (approximately 900 TMs per day, at a traveling distance of approximately 700 miles per shipment). This local increase of TMs accounts for approximately 10% of the increase in TMs and additional secondary negative impacts on the whole SC.

For the microchip SC, the maximum increase of TLs was found on the route between the chemical plant of Versum Materials U.S. at Phoenix, AZ and the fab of Intel at Chandler, AZ, with an increase of 226,593 TLs (from 23,624 to 250,217) over the 2-year study period. The added TLs (equivalent to approximately 54 trucks per hour) would be expected to increase traffic congestion (maximum SRI increase from 2.71 to 4.12) on roads connecting these two locations. Accordingly, this road section will bear nearly all the added TLs and corresponding secondary negative impacts. The maximum TM increase is found on the route between the chemical plant of Versum Materials U.S. in Phoenix and the fab of Intel in Chandler, with an increase of 2 million TMs over the 2-year study period (3,922 TMs per day at a traveling distance of 10 miles per shipment).

Generally, microchip SC reshoring has greater negative impact at the local level (e.g., additional 54 trucks per hour between one O-D pair) than does the reshoring of the manufacturing of N95 FFRs (e.g., with an additional 1 truck per hour between one O-D). The difference can be explained by the fact that substantially greater raw material requirements (especially chemicals and raw wafers) by volume are required than that (primarily crude oil) required in N95 FFR SC reshoring. Additionally, the microchip customers, chemical suppliers, raw wafer suppliers, fabs, distributors and assembly, testing, and packaging (ATP) plants and plant locations are clustered at relatively few locations (i.e., AZ, especially the Phoenix Metropolitan area, and TX), fostering more consolidated, larger shipments. This cluster pattern (compact design) was shown to be advantageous in (Patil, 2021). This differs from the N95 FFR SC case, where middle product manufacturers and end customers are scattered over many locations across the nation, creating a need for many smaller shipments.

An increase in inbound raw material flows can also be expected at some of the largest U.S. ports. For example, an increase in inbound flows of 52,540 tons of crude oil and 5,990 tons of raw wafers could be expected to pass through the ports in Houston and Los Angeles, respectively, over the study period to support the increased domestic production associated with the studied scenario. Such increases account for 0.02% and 0.01% of the total tonnages handled in the ports in 2017, respectively (USACE, 2020).

Table 1. Maximum local impacts of N95 and microchip SC reshoring.

Scenario		N95 FFR			Microchips		
Impact		Existing	Post-reshoring	Increase	Existing	Post-reshoring	Increase
TMs (millions)		0.0	0.5	0.5	0.2	2.3	2.0
TLs		1,112	4,582	3,470	23,624	250,217	226,593
Traffic congestion (Maximum SRI)		2.56	2.59	0.03	2.71	4.12	1.41
Maintenance cost ($ millions)		0.0	0.2	0.2	0.1	0.8	0.7
Fuel consumption (million gallons)		0.0	0.2	0.2	0.1	0.7	0.7
Pollutant (1,000s of tons)	CO	0.0	0.0	0.0	0.0	0.0	0.0
	CO_2	0.0	1.7	1.7	0.8	8.3	7.5
	VOC	0.0	0.0	0.0	0.0	0.0	0.0
	NOx	0.0	0.0	0.0	0.0	0.1	0.1
	PM_{10}	0.0	0.0	0.0	0.0	0.0	0.0
	SOx	0.0	0.0	0.0	0.0	0.0	0.0

National level impacts

As revealed in Table 2, the reshoring of the manufacturing of both N95 FFR and microchip SCs is expected to have negative impacts on the larger, national transportation system. N95 FFR SC reshoring is expected to lead to greater added TMs (4.14 million in Table 2) and result in substantial added maintenance costs, fuel consumption, and air pollutant emission, while the microchip SC reshoring is expected to result in greater added TLs (229,510 in Table 2). The large increase of TMs at the national level in N95 FFR reshoring is attributed to the scattered entity location pattern in the SC as well. The large increase of TLs from the reshoring of the microchip SC is also a consequence of substantially greater raw material requirements in this SC. On the other hand, the compact design in the microchip SC reshoring case enabled through consolidation of raw material and middle product supplier to a single region is expected to lead to a lower increase at 0.6% in TMs compared with that of N95 FFRs at 93%. In total, reshoring both SCs would add 4.5 million TMs and 0.2 million TLs to the nation’s roadways over the 2-year study period.

Table 2. Aggregated nation-wide impacts of N95 and microchip SC reshoring.

Scenario		N95 FFR			Microchips			
Impact		Existing	Post-reshoring	Increase	Existing	Post-reshoring	Increase	Total scenario
TMs (millions)		4.48	8.62	4.14	49.14	49.46	0.32	4.46
TLs		26,070	33,630	7,560	183,530	413,040	229,510	237,070
Maintenance cost ($ millions)		1.57	3.02	1.45	17.20	17.31	0.11	1.56
Fuel consumption (million gallons)		1.48	2.9852	1.37	16.22	16.32	0.11	1.48
Pollutant (thousands of tons)	CO	0.03	0.06	0.03	0.36	0.36	0	0.03
	CO_2	16.44	31.62	15.18	180.19	181.37	0.18	15.36
	VOC	0.01	0.02	0.01	0.10	0.10	0.00	0.01
	NOx	0.22	0.42	0.20	2.38	2.40	0.02	0.22
	PM_{10}	0.01	0.01	0.01	0.08	0.08	0.00	0.01
	SOx	0.01	0.01	0.01	0.06	0.06	0.00	0.01

Evaluating the Effects of Reshoring on National Resilience via the NRE Module

In 2020, the first year of the COVID-19 pandemic, the average cost of an imported N95 FFR was over $1.5 (U.S. Census Bureau, 2021). This price dropped to 30¢ in 2021 when domestic N95 FFR production expanded dramatically (USITC, 2020). With avoided economic losses on the order of $2.3 billion, national resilience improvement from reshoring of the N95 FFRs for the tested scenario was estimated to be 0.54 by equation (4).

Unlike N95 FFRs that serve only as end products, microchips are incorporated into many other products. Thus, economic losses due to shortages in microchips can have wide-scale impact that can require analysis and data across many products and industries. In this study, only the economic loss in the microchip industry is estimated for resilience evaluation. A linear unit price function for microchips is built based on the sales data from 2016 to 2021 in reports from the Semiconductor Industry Association (SIA) (SIA, 2020; SIA, 2021b). With $50.6 billion in avoided economic losses, national resilience improvement was estimated to be 1.0 by equation (4), meaning that 100% of the potential economic losses in the SC would be avoided. Details of these estimates are provided in "Supplementary Appendix B." In total, this two-product SC reshoring scenario would lead to a combined $52.9 billion in avoided economic losses or a 0.96-point increase in national resilience improvement, inferring that 96% of the potential economic losses in the two SCs would be avoided as a result of reshoring and/or increasing domestic production.

The gains In national resilience measured through this evaluation methodology directly considered aspects of unfulfilled demand that can be reduced by SC reshoring through supplier management and enhanced government control (e.g., via government-based incentives), the first and last of the four mechanisms by which unfulfilled demand can be reduced, as discussed in Chapter 3.

Tradeoff Analysis via the IRTE Module

The cost of improvements in national resilience by 0.54 points achieved by reshoring the manufacturing of N95 FFRs alone was estimated to create a 0.001% increase in the 300 billion national total TMs estimated in 2019 (National Center for Statistics and Analysis, 2021), but with trivial local impact. The expected TM increase and corresponding negative impacts induced by increased domestic production of microchips and related SC restructuring was found to be even smaller than that induced by the N95 FFR SC reshoring portion of the scenario, while the maximum national resilience improvement was obtained (with a value of 1).

In considering the reshoring of the manufacturing of the microchip SC, the gains in national resilience likely outweigh the expected incurred negative impacts. Given the perfect (1.0) resilience level achieved through reshoring, by the tradeoff curve in Chapter 3, further increasing domestic production of microchips would have nominal impact on national resilience, but would produce added negative impacts. Gains would be obtained only by exporting surplus and thus increasing GDP. The benefits of surplus could improve resilience for future demand surge scenarios, the value of which would require re-evaluation under the new scenario. On the contrary, with the estimated N95 FFR demand and a resilience value of only 0.54 (of 1.0), additional improvement in national resilience can be gained through further increase in domestic production capacity. Until a level of 1.0 is reached, the gains in national resilience may continue to outweigh the added negative impacts.

Other economic benefits of reshoring, such as boosting the domestic economy, reducing port congestion, increasing the number of domestic jobs, and improving SC security (e.g., less lead time, higher service level) are also nontrivial. A total of $2.2 billion and $34.7 billion value would be created by reshoring the N95 FFR SC and microchip SC, respectively. Additionally, savings from reducing imports can be expected. Note that $2.8 billion was spent to import 1.8 billion of N95 FFR in 2021 (USITC, 2021). In addition, the reshoring of these critical medical supplies can bring job opportunities. For example, a single N95 FFR plant that produces 5 million units of N95 FFRs a month can create around 500 new jobs (Stoney, 2020). Through expanding the N95 FFR plants alone, the creation of more than 13,000 jobs could be expected from reshoring (monthly capacity increasing from 42.5 million to 173 million by reshoring). The reshoring of the microchip SC is expected to more than double the current approximately 184,600 U.S. microchip industry jobs (Platzer et al., 2020) by directly creating approximately 235,000 new jobs, and support an additional 1.4 million jobs indirectly throughout the U.S. economy (SIA, 2021b).

National Readiness

To assess national readiness for undertaking a large-scale reshoring proposal within the United States, a method for estimating the impacts of reshoring at scale, involving numerous industries, is required. Two such approaches were considered: (1) a commodity market-value based method that scales from detailed analyses of specific products (here, N95 FFRs and microchips) and (2) a raw-material equivalent (RME) approach that estimates TLs and TMs as a function of the raw materials that are used as a result of increased production.

Scenario-based scaling

"New normal" and "stretch" reshoring scenarios for the U.S. manufacturing sector for the year 2025 proposed in (Ramaswamy et al. 2017) are used here to set target scaling levels. In the "new normal" scenario, it was assumed that the United States would maintain its 2015 level of domestic production of finished goods in terms of market share into 2025, despite what was revealed to be a declining trend in manufacturing. To maintain the 2015 share of the global market, domestic production would need to increase to meet the projected growth in product demand. It was estimated that this increase would create $300 billion in added product value. In the "stretch" scenario, the value added was estimated at $530 billion. In this section, the two approaches to estimate the scaled impact on U.S. roadways from reshoring at a national level are based on these added values for the "new normal" and "stretch" scenarios.

Scenario-based scaling here builds on the N95 FFR and microchip scenario of Chapter 4. The U.S. N95 FFR market value in 2019 was $600 million with a demand of 445 million units (David and DeCarlo, 2020) or $1.30 per piece. 2019 is used here to predate the extraordinary demand and price surges from the COVID-19 pandemic. In the reshoring N95 FFR scenario, where all demand is satisfied by domestic production after reshoring, $2.2 billion in market value would be added. Thus, a $300 billion market value increase as expected in the "new normal" scenario for the whole nation would lead to 136 times (300/2.2) more TMs and TLs than estimated for reshoring N95 FFRs. A similar approach was used for scaling the microchip SC. The added TMs, TLs, and secondary impacts, including fuel consumption, emissions of GHGs and other air pollutants, and hazmat property damage only (PDO) crashes (the key impact indices used herein), arising under the "new normal" and "stretch" reshoring scenarios, are provided in Table 3.

Compared to general imported commodities, both N95 FFRs and microchips are high-value, low-weight, and low-volume products. Thus, fewer TLs are required for their transport by value. Consequently, the negative externalities estimated by this value-based scaling approach with base products of N95 FFRs or microchips can only provide a lower bound on the negative impacts for the transportation system.

With scaling based on N95 FFR SC, reshoring of "all-N95 FFR-alike" under the "new normal" would only lead to a 0.1% increase in national total TMs with trivial increase of TLs and secondary negative impact increase of similar magnitude. Similarly, scaling based on microchips produces a 0.2% increase of 589 million annual TLs nationally (estimated by taking the national total tons shipped by truck of 8,843 million tons and dividing by the national average of 15 tons per TL from 2017 data (USDOT et al., 2020)) with an expected small increase in TMs and corresponding trivial secondary negative impacts.

Table 3. Impact of large-scale critical reshoring (per year).

Impact	"New Normal" Scenario			"Stretch" Scenario		
	Scaling from N95 FFR	Scaling from microchip	Scaling total with RME	Scaling from N95 FFR	Scaling from microchip	Scaling total with RME
Economic ($billions)	300	300	300	530	530	530
Raw materials (million tons)	\	\	645	\	\	1,141
TMs (millions)	284	1	8,812	501	2	15,591
TLs (thousands)	507	991	43,000	895	1,751	76,000
Maintenance costs ($millions)	99	0	3,084	175	1	5,457
Fuel consumption (million gallon)	94	0	2,908	165	1	5,145
CO (thousand tons)	2	0	64	4	0	114
CO_2 (thousand tons)	1,040	5	32,315	1,837	9	57,172
VOC (thousand tons)	1	0	19	1	0	33
NO_x (thousand tons)	14	0	427	24	0	756
PM (thousand tons)	0	0	14	1	0	25
SO_x (thousand tons)	0	0	11	1	0	19
HAZMAT PDO crash	141	2	1,032	250	3	1,826

Raw material equivalent-based scaling

The added product values for "new normal" and "stretch" scenarios are 13% (300/2,300) and 23% (530/2,300), respectively, of the total $2.3 trillion in U.S. imported commodities, including products and raw materials, based on data from 2015 (UN, 2021). The volume of raw materials that is needed to produce these imported commodities (raw material equivalent (RME)) is calculated here to be 4.96 billion tons (based on annual numbers given by (IRP, 2018)) in 2015. If 13% ("new normal") and 23% ("stretch") of these materials are to be handled within the United States as a result of general large-scale reshoring, then the additional raw material to be transported within U.S. borders would be 645 million tons (13% of 4.96 billion tons) and 1,141 million tons (23% of 4.96 billion tons), respectively. With an average of 206 miles per shipment by truck and 15 tons per TL in 2017 (USDOT et al., 2020), the added TLs, TMs, and the secondary impacts induced by these two reshoring scenarios were estimated and are given in Table 3.

Using the "new normal scenario," at a national level, reshoring would lead to an additional 43 million TLs and 8.812 billion TMs (3% of the national total TMs in 2019), with the secondary impacts of similar magnitude, and likely very significant impact to some local areas. This is much higher than the estimates obtained for the "all-N95 FFR-alike" and "all-microchips-alike" scaling approaches.

National readiness for large-scale reshoring

The general large-scale "new-normal" scenario of many different industries proposed in (Ramaswamy et al., 2017) is estimated here to cause a 3% increase in TMs, a 2% increase in national total transportation-based GHG emissions (estimated at 1,848 million tons of GHG emissions in 2017 (Office of Transportation and Air Quality, 2021)), and other negative impacts of similar magnitude. As the truck industry constitutes a 1.7% share of the GDP (USDOT and USBTS, 2019), a 3% increase in TMs from this industry would not likely be difficult to absorb in many locations. However, the impacts at some locations, especially in cities with developed transportation networks and large labor forces, may be unacceptable. With 43% of U.S. public roadways in poor or mediocre condition (ASCE, 2021), the added freight TLs and TMs, along with the resulting negative impacts from this added truck traffic, may be difficult for some roadways to support.

There is also a need to consider the changes in GHG emissions from a global perspective. Added domestic GHG emissions from the large-scale reshoring estimation herein would account for 0.6% of domestic total emissions from all sectors (EPA, 2022). While not a large percentage of the total, as the world seeks to reduce GHG emissions to combat climate change and aims for carbon neutrality, any increase could counter these decarbonization efforts. However, it is possible that with greater domestic control of industrial processes and sourcing for supporting power generation, total global emissions per unit of production could decrease. Deeper analyses of emissions production from current global operations would be required to make this assessment.

CHAPTER 5

Recommendations

SUMMARY

This research was motivated by the question, “Can our civil infrastructure support U.S.-based production increase from reshoring should we bring manufacturing back to the U.S.?” To answer this question, a quantitative evaluation framework was developed for estimating the impact and national resilience improvements resulting from a proposed SC reshoring scenario involving two critical products from two industries: N95 FFRs and microchips. Two methods for estimating U.S. readiness for large-scale reshoring in the manufacturing of products from a broad array of sectors were also developed.

FINDINGS

Results from application of the evaluation framework to a scenario of critical products (N95 FFRs and microchips) show that the reshoring of the manufacturing of these products can have significant benefits in terms of improving national resilience and other economic indicators. However, in the case of microchips, the potential for negative impacts in some locations may be significant, and the gains may not outweigh the negative impacts. In considering large-scale reshoring, the potential for negative impact may be very substantial. This is especially problematic for locations in which the production activities are concentrated, as well as along roadways that would handle the movement of not only end products, but raw materials and middle products. Thus, on the one hand, the existing U.S. transportation infrastructure should be sufficient and ready for large-scale reshoring efforts, and the gains in national resilience, and for the economy more generally, could be very substantial. Generally, the benefits are likely to outweigh the negative impacts for the infrastructure. On the other hand, the burden of such transformation will likely be borne by local areas and their surrounding communities.

Conducting detailed impact analysis as was completed here for the two studied products under given assumptions requires significant data collection and modeling effort. Publicly available data were used in this analysis. More accurate computations can be made with specific data from individual manufacturing firms on SC structure, alternative suppliers, operations, transportation contracts, proposed reshoring designs and locations, and more.

OPPORTUNITIES FOR FUTURE RESEARCH

This study included the transport of materials and products only along roadways, which generally represents over 70% of national freight movements by both value and weight (USDOT et al., 2020). Changes in flows at ports was also provided. With minor modifications, this framework can incorporate other modes, especially rail, and multi-modal systems. Additionally, other dimensions of national resilience, beyond reduced economic losses, can be considered if measured. Consider, for example, numbers of lives saved through enhanced access to medical protective gear (N95 FFRs) or equity increase due to improved access to affordable electronic devices.

There are also concerns that moving production of critical goods to one location (e.g., the United States) may actually lead to lower resilience (Christopher and Peck, 2004). For example, reshoring some key pharmaceutical and medical device industries to Puerto Rico led to a nationwide critical drug shortage when this site was hit by Hurricane Maria in 2017 (Sacks et al., 2018). In fact, having multiple production sites is a known approach for increasing resilience (Christopher and Peck, 2004). This aspect was not included in the national resilience improvement analysis herein. Other concerns that could be considered in reshoring initiatives evaluation include the potential for diminishing demand, labor costs, and inflation.

Last, the analysis of U.S. infrastructure readiness for large-scale reshoring might also include impacts on non-transportation infrastructure systems, including utilities (water, power, and waste material handling), natural resources, and industrial waste.

References

Afrin, T., Yodo, N., 2020. A Survey of Road Traffic Congestion Measures towards a Sustainable and Resilient Transportation System. Sustainability 12, 46–60. https://doi.org/10.3390/su12114660.

Ali, I., Sadiddin, A., Cattaneo, A., 2022. Risk and resilience in agri-food supply chain SMEs in the pandemic era: a cross-country study. International Journal of Logistics Research and Applications 1–19. https://doi.org/10.1080/13675567.2022.2102159.

ASCE, 2021. National Infrastructure Report Card 2021 report. ASCE.

Atallah, S.S., Gómez, M.I., Björkman, T., 2014. Localization effects for a fresh vegetable product supply chain: Broccoli in the eastern United States. Food Policy 49, 151–159. https://doi.org/10.1016/j.foodpol.2014.07.005.

Bailey, D., De Propris, L., 2014. Reshoring: Opportunities and Limits for Manufacturing in the UK – the case of the Auto Sector. Revue d'économie industrielle 45–61. https://doi.org/10.4000/rei.5732.

Capri, A., 2020. Semiconductors at the Heart of the US-China Tech War 90.

Chacon-Hurtado, D., Kumar, I., Gkritza, K., Fricker, J.D., Beaulieu, L.J., 2020. The role of transportation accessibility in regional economic resilience. Journal of Transport Geography 84, 102695. https://doi.org/10.1016/j.jtrangeo.2020.102695.

Chen, Q., E. Miller-Hooks, E. Huang, "Assessing Transportation Infrastructure Impacts from Supply Chain Restructuring for Increased Domestic Production of Critical Resources," in review.

Christopher, M., Peck, H., 2004. Building the Resilient Supply Chain. The International Journal of Logistics Management 15, 1–14. https://doi.org/10.1108/09574090410700275.

Cohen, M.A., Cui, S., Ernst, R., Huchzermeier, A., Kouvelis, P., Lee, H.L., Matsuo, H., Steuber, M., Tsay, A.A., 2018. OM Forum—Benchmarking Global Production Sourcing Decisions: Where and Why Firms Offshore and Reshore. M&SOM 20, 389–402. https://doi.org/10.1287/msom.2017.0666.

David, A., DeCarlo, S., 2020. COVID-19 Related Goods: The U.S. Industry, Market, Trade, and Supply Chain Challenges (No. 5145). United States International Trade Commission.

Dormady, N.C., Rose, A., Roa-Henriquez, A., Morin, C.B., 2022. The cost-effectiveness of economic resilience. International Journal of Production Economics 244, 108371. https://doi.org/10.1016/j.ijpe.2021.108371.

Doroudi, R., Azghandi, R., Feric, Z., Mohaddesi, O., Sun, Y., Griffin, J., Ergun, O., Kaeli, D., Sequeira, P., Marsella, S., Harteveld, C., 2018. An integrated simulation framework for examining resiliency in pharmaceutical supply chains considering human behaviors, in: 2018

Winter Simulation Conference (WSC). Presented at the 2018 Winter Simulation Conference (WSC), pp. 88–99. https://doi.org/10.1109/WSC.2018.8632387.

Ellram, L.M., Tate, W.L., Petersen, K.J., 2013. Offshoring and Reshoring: An Update on the Manufacturing Location Decision. Journal of Supply Chain Management 49, 14–22. https://doi.org/10.1111/jscm.12019.

Encyclopedia, 2021a. GlobalFoundries. Wikipedia.

Encyclopedia, 2021b. List of semiconductor fabrication plants. Wikipedia.

Engstrom, T., Baliunas, D.O., Sly, B.P., Russell, A.W., Donovan, P.J., Krausse, H.K., Sullivan, C.M., Pole, J.D., 2021. Toilet Paper, minced meat and diabetes medicines: Australian panic buying induced by COVID-19. International Journal of Environmental Research and Public Health 18, 6954.

Entegris, 2020. SB300 FOSB for 300 mm Wafers 14.

Evstatieva, M., 2021. U.S. Companies Shifted to Make N95 Respirators During COVID. Now, They're Struggling. NPR.

Executive office of the President Office of Management and Budget, 2017. 2017_NAICS_Manual.

Fjäder, C., 2014. The nation-state, national security and resilience in the age of globalisation. Resilience 2, 114–129. https://doi.org/10.1080/21693293.2014.914771.

Flaherty, N., 2021. Top five chip makers dominate global wafer capacity [WWW Document]. eeNews Europe. URL https://www.eenewseurope.com/news/top-five-chip-makers-dominate-global-wafer-capacity (accessed 11.1.21).

Foerstl, K., Kirchoff, J.F., Bals, L., 2016. Reshoring and insourcing: drivers and future research directions. International Journal of Physical Distribution & Logistics Management 46, 492–515. https://doi.org/10.1108/IJPDLM-02-2015-0045.

Fratocchi, L., Ancarani, A., Barbieri, P., Di Mauro, C., Nassimbeni, G., Sartor, M., Vignoli, M., Zanoni, A., 2016. Motivations of manufacturing reshoring: an interpretative framework. International Journal of Physical Distribution & Logistics Management 46, 98–127. https://doi.org/10.1108/IJPDLM-06-2014-0131.

Global Wafer Capacity 2021-2025, 2020. IC Insights.

Gould, J., 2022. As semiconductor shortages linger, one defense firm gets creative. Defense News. Available at: https://www.defensenews.com/pentagon/2022/09/22/as-semiconductor-shortages-linger-one-defense-firm-gets-creative/ (accessed 10.23.22).

Gray, J.V., Skowronski, K., Esenduran, G., Johnny Rungtusanatham, M., 2013. The Reshoring Phenomenon: What Supply Chain Academics Ought to know and Should Do. Journal of Supply Chain Management 49, 27–33. https://doi.org/10.1111/jscm.12012.

Gurvich, V.J., Hussain, A.S., 2020. In and Beyond COVID-19: US Academic Pharmaceutical Science and Engineering Community Must Engage to Meet Critical National Needs. AAPS PharmSciTech 21, 153. https://doi.org/10.1208/s12249-020-01718-9.

Harada, L.L., 2010. Semiconductor Technology and U.S. National Security: Defense Technical Information Center, Fort Belvoir, VA. https://doi.org/10.21236/ADA526581.

Ho, W., Zheng, T., Yildiz, H., Talluri, S., 2015. Supply chain risk management: a literature review. International Journal of Production Research 53, 5031–5069. https://doi.org/10.1080/00207543.2015.1030467.

Hohenstein, N.-O., Feisel, E., Hartmann, E., Giunipero, L., 2015. Research on the phenomenon of supply chain resilience: A systematic review and paths for further investigation. International Journal of Physical Distribution & Logistics Management 45, 90–117. https://doi.org/10.1108/IJPDLM-05-2013-0128.

Hosseini, S., Ivanov, D., Dolgui, A., 2019. Review of quantitative methods for supply chain resilience analysis. Transportation Research Part E: Logistics and Transportation Review 125, 285–307. https://doi.org/10.1016/j.tre.2019.03.001.

International Resource Panel (IRP), 2018. Global Material Flows Database.

Jüttner, U., Peck, H., Christopher, M., 2003. Supply chain risk management: outlining an agenda for future research. International Journal of Logistics Research and Applications 6, 197–210. https://doi.org/10.1080/13675560310001627016.

Kamalahmadi, M., Parast, M.M., 2016. A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research. International Journal of Production Economics 171, 116–133. https://doi.org/10.1016/j.ijpe.2015.10.023.

Keelan, K., Printezis, A., Blackmer, C., Department of Finance, Department of Supply Chain Management, Barrett, The Honors College, 2021. Reshoring Manufacturing Post Covid-19: Building a more Resilient United States Healthcare Supply Chain, in: Barrett, The Honors College Thesis/Creative Project Collection, Academic Year 2020-2021.

Khan, S., 2021. The Semiconductor Supply Chain: Assessing National Competitiveness. Center for Security and Emerging Technology. https://doi.org/10.51593/20190016

Kinkel, S., 2014. Future and impact of backshoring—Some conclusions from 15 years of research on German practices. Journal of Purchasing and Supply Management 20, 63–65. https://doi.org/10.1016/j.pursup.2014.01.005.

Kleindorfer, P.R., Saad, G.H., 2009. Managing Disruption Risks in Supply Chains. Production and Operations Management 14, 53–68. https://doi.org/10.1111/j.1937-5956.2005.tb00009.x.

Lammers, D., 2003. EETimes - Texas Instruments to keep next 300mm-wafer fab close to home. Available at: https://www.eetimes.com/texas-instruments-to-keep-next-300mm-wafer-fab-close-to-home/ (accessed 11.1.21).

Leprince-Ringuet, D., 2021. The impact of the global chip shortage continues to ripple across the tech supply chain. ZDNet. Available at: https://www.zdnet.com/article/the-impact-of-the-global-chip-shortage-continues-to-ripple-across-the-tech-supply-chain/ (accessed 12.16.22).

Lieberman, J.I., 2003. National Security Aspects of the Global Migration of the U.S. Semiconductor Industry.

Lincicome, S., 2021. Manufactured Crisis: "Deindustrialization," Free Markets, and National Security 61.

Meyer, M.D., McLeod, S., Fidell, T., Gajjar, H., Sood, D., Kamali, M., Wingate, R., Willauer, D.O., Southworth, F., 2019. Freight Transportation Resilience in Response to Supply Chain Disruptions 165.

Miller-Hooks, E., Chen, Q., Huang, E. 2022. Transportation Infrastructure Readiness for Post-Pandemic Supply Chain Transformation for Greater Resilience: Part 1 – Impact Analysis. Technical Report, Center for Integrated Asset Management for MultiModal transportation Infrastructure Systems (CIAMTIS), USDOT Region 3 University Transportation Center, December 2022.

Moore, C.J., 2021. Chip shortage will cost industry $210B, 7.7M units in 2021, Alix Partners says. Automotive News. Available at: https://www.autonews.com/manufacturing/ alixpartners-says-chip-shortage-will-cost-auto-industry-210b-77m-units-2021 (accessed 4.11.22).

Moorhead, P., 2019. On Semiconductor and Globalfoundries Both Win With Its $430M Fab 10 Deal. Available at: https://www.forbes.com/sites/patrickmoorhead/2019/05/15/on-semiconductor-and-globalfoundries-both-win-with-its-430m-fab-10-deal/ (accessed 11.1.21).

Moser, H., Kelley, M., 2022. Multiple Supply Chain Risks Accelerate Reshoring, Reshoring Initiative IH 2022 Data Report. Reshoring Initiative.

Munson, C.L., Rosenblatt, M.J., 1999. The Use and Abuse of Power in Supply Chains. Business Horizons 42, 55. https://doi.org/10.1016/S0007-6813(99)80049-4.

Narassima, M.S., Anbuudayasankar, S.P., Mathiyazhagan, K., Ganesh, K., Lee, T.-R. (Jiun-S., 2022. Supply chain resilience: conceptual model building and validation. International Journal of Logistics Research and Applications 1–33. https://doi.org/10.1080/13675567.2022.2056584

Nicholson, C.F., Gómez, M.I., Gao, O.H., 2011. The costs of increased localization for a multiple-product food supply chain: Dairy in the United States. Food Policy 36, 300–310. https://doi.org/10.1016/j.foodpol.2010.11.028.

New Jersey Economic Development Authority (NJEDA), 2021. Personal Protective Equipment (“PPE”) Manufacturing Tax Credit (NEW). NJEDA. Available at: https://www.njeda.com/ppe/ (accessed 12.16.22).

Orzes, G., Sarkis, J., 2019. Reshoring and environmental sustainability: An unexplored relationship? Resources, Conservation and Recycling 141, 481–482. https://doi.org/10.1016/j.resconrec.2018.11.004.

Ottemöller, O., Friedrich, H., 2019. Modelling change in supply-chain-structures and its effect on freight transport demand. Transportation Research Part E: Logistics and Transportation Review 121, 23–42. https://doi.org/10.1016/j.tre.2017.08.009.

Patil, C.A., 2021. The Semiconductor Manufacturing Cluster. #chetanpatil - Chetan Arvind Patil. https://www.chetanpatil.in/the-semiconductor-manufacturing-cluster/ (accessed 12.16.22).

Platzer, M.D., Jr, J.F.S., Sutter, K.M., 2019. Semiconductors: U.S. Industry, Global Competition, and Federal Policy (No. R46581). Congressional Research Service.

Ponomarov, S.Y., Holcomb, M.C., 2009. Understanding the concept of supply chain resilience. Journal of Purchasing 20, 124–143. https://doi.org/10.1108/09574090910954873

Ramaswamy, S., Manyika, J., Pinkus, G., George, K., 2017. making-it-in-america-revitalizing-us-manufacturing-full-report.pdf. McKinsey Global Institute.

Retter, L., Frinking, E., Hoorens, S., Lynch, A., Nederveen, F., Phillips, W., 2020. Relationships between the economy and national security: Analysis and considerations for economic security policy in the Netherlands. RAND Corporation. https://doi.org/10.7249/RR4287.

Robertson, J., 2003. EETimes - Micron fab could ramp quickly for 300-mm wafers. EETimes. Available at: https://www.eetimes.com/micron-fab-could-ramp-quickly-for-300-mm-wafers/ (accessed 11.1.21).

Rose, A., 2007. Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions. 7, 383–398. https://doi.org/10.1016/j.envhaz.2007.10.001

Sacks, C.A., Kesselheim, A.S., Fralick, M., 2018. The Shortage of Normal Saline in the Wake of Hurricane Maria. JAMA Intern Med 178, 885. https://doi.org/10.1001/jamainternmed.2018.1936

SafeRack's Industrial Index, 2020. Fuel Transport Safety - Truck Tanker Types | SafeRack's Industrial Index. SafeRack. Available at: https://www.saferack.com/glossary/cargo-tanks-transport-safety/ (accessed 6.16.21).

Sarder, M., Miller, C., Sulbaran, T., Golias, M., Anderson, M., Zietlow, B., Mishra, S., University of Southern Mississippi, 2016. Reshoring and its impact on transportation infrastructure & US economy. (No. CFIRE 09-13).

Shih, W.C., 2014. What It Takes to Reshore Manufacturing Successfully. MIT Sloan Management Review. Available at: https://sloanreview.mit.edu/article/what-it-takes-to-reshore-manufacturing-successfully/ (accessed 12.16.22).

Shilov, A., 2020. 5nm in the USA: TSMC's Board Approves $3.5 Billion Fab in Arizona. Tom's Hardware. Available at: https://www.tomshardware.com/news/tsmc-arizona-fab-investment (accessed 12.16.22).

Semiconductor Industry Association (SIA), 2020. 2020 State of the U.S. Semiconductor Industry. Semiconductor Industry Association.

Semiconductor Industry Association (SIA), 2021a. 2021 SIA Factbook. Semiconductor Industry Association .

Semiconductor Industry Association (SIA), 2021b. 2021 State of the U.S. Semiconductor Industry. Semiconductor Industry Association.

Sirkin, H.L., Zinser, M., Hohner, D., Rose, J., 2012. U.S. Manufacturing Nears the Tipping Point: Which Industries, Why, and How Much? The Boston Consulting Group (BCG).

Sohn, J., 2021. WSJ News Exclusive | Samsung to Choose Taylor, Texas, for $17 Billion Chip-Making Factory. Wall Street Journal.

Stoney, A., 2020. Honeywell hiring 500 in Phoenix to help manufacture N95 masks for coronavirus fight. The Arizona Republic. Available at: https://www.azcentral.com/story/news/local/phoenix/2020/03/30/honeywell-hiring-phoenix-manufacture-n-95-masks/5092694002/ (accessed 12.16.22).

Taiwan Semiconductor Manufacturing Company Limited (TSMC), 2020. TSMC 2019 Annual Report. TSMC.

Tang, C.S., 2005. Perspectives in Supply Chain Risk Management: A Review. International Journal of Production Economics. https://doi.org/10.2139/ssrn.925274.

Tang, O., Nurmaya Musa, S., 2011. Identifying risk issues and research advancements in supply chain risk management. International Journal of Production Economics 133, 25–34. https://doi.org/10.1016/j.ijpe.2010.06.013.

Tate, W.L., Ellram, L.M., Schoenherr, T., Petersen, K.J., 2014. Global competitive conditions driving the manufacturing location decision. Business Horizons 57, 381–390. https://doi.org/10.1016/j.bushor.2013.12.010.

The White House, 2022. Remarks of President Joe Biden – State of the Union Address As Prepared for Delivery. The White House. Available at: https://www.whitehouse.gov/briefing-room/speeches-remarks/2022/03/01/remarks-of-president-joe-biden-state-of-the-union-address-as-delivered/ (accessed 4.11.22).

Tomlin, B., 2006. On the Value of Mitigation and Contingency Strategies for Managing Supply Chain Disruption Risks. Management Science 52, 639–657. https://doi.org/10.1287/mnsc.1060.0515.

United Nations (UN), 2021. Annual International Trade Statistics by Country. Available at: Trend Economy. https://trendeconomy.com/data/h2/UnitedStatesOfAmerica/ (accessed 12.16.22).

U.S. Army Corps of Engineers (USACE), 2020. WCSC Waterborne Commerce Statistics Center. Available at: https://www.iwr.usace.army.mil/About/Technical-Centers/WCSC-Waterborne-Commerce-Statistics-Center-2/ (accessed 12.2.22).

U.S. Center for Disease Control (USCDC), 2020. Strategies for Optimizing the Supply of N95 Respirators. Coronavirus Disease 2019 (COVID-19). Available at: https://www.cdc.gov/coronavirus/2019-ncov/hcp/respirators-strategy/index.html (accessed 12.16.22).

U.S. Census Bureau, 2021. Census Bureau Home Page. Available at: https://usatrade.census.gov/ (accessed 10.14.22).

U.S. Census Bureau, 2012. Statistical Abstract of the United States: 2012. U.S. Census Bureau.

U.S. Department of Defense (USDOD), 2020. DOD Awards $126 Million Contract to 3M, Increasing Production of N95 Masks. U.S. Department of Defense. Available at: https://www.defense.gov/Newsroom/Releases/Release/Article/2178152/dod-awards-126-million-contract-to-3m-increasing-production-of-n95-masks/ (accessed 12.16.22).

U.S. Department of Transportation (USDOT), U.S. Bureau of Transportation Statistics (USBTS), 2019. Freight Facts and Figures. Available at: https://data.bts.gov/stories/s/Freight-Transportation-the-Economy/6ix2-c8dn/ (accessed 12.16.22).

U.S. Department of Transportation (USDOT), U.S. Bureau of Transportation Statistics, U.S. Department of Commerce, and U.S. Census Bureau, 2017 Commodity Flow Survey, 2020. 2017 Economic Census: Transportation, (No. EC17TCF-US).

U.S. Environmental Protection Agency (USEPA), 2022. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020 (No. EPA 430-R-22-003). U.S. Environmental Protection Agency.

U.S. International Trade Commission (USITC), 2021. dataweb.usitc.gov. Available at: https://dataweb.usitc.gov/login?return=%2Ftrade%2Fsearch%2FImport%2FNAIC (accessed 12.16.22).

van Hoek, R., Dobrzykowski, D., 2021. Towards more balanced sourcing strategies – are supply chain risks caused by the COVID-19 pandemic driving reshoring considerations? Supply Chain Management: An International Journal 26, 689–701. https://doi.org/10.1108/SCM-09-2020-0498.

Wiesmann, B., Snoei, J.R., Hilletofth, P., Eriksson, D., 2017. Drivers and barriers to reshoring: a literature review on offshoring in reverse. EBR 29, 15–42. https://doi.org/10.1108/EBR-03-2016-0050.

Williams, N., 2020. An Analysis of the Operational Costs of Trucking: 2020 Update. American Transportation Research Institute.

Wilson, M.C., 2007. The impact of transportation disruptions on supply chain performance. Transportation Research Part E: Logistics and Transportation Review 43, 295–320. https://doi.org/10.1016/j.tre.2005.09.008.

Wu, D., King, I., 2020. TSMC Wins Approval From Phoenix for $12 Billion Chip Plant. Bloomberg.com.

Zhai, W., Sun, S., Zhang, G., 2016. Reshoring of American manufacturing companies from China. Operations Management Research 9, 62–74. https://doi.org/10.1007/s12063-016-0114-z.

APPENDIX A

Procedures and Results of Applying SC-RI to a Microchip SC

The manufacturing of microchips is complex, involving thousands of suppliers and hundreds of different raw materials or middle products. For simplicity and feasibility of this study, microchip manufacturing processes were categorized into three key areas: (1) design, (2) front-end fabrication in a semiconductor fabrication plant (fab), and (3) back-end ATP (Platzer et al., 2020). Key elements of the microchip SC based in the United States, including entities and commodity flows involved in fab, were included in this analysis. The end product of the microchip SC is the semiconductor wafer (SMEW). The ATP plants (ATPPs) are assumed to be the end customers. For the existing microchip SC, the capacity of domestic fabs was set equal to the related domestic capacity at the end of 2020 (0.73 million 12-inch equivalent wafers per month (IC Insights, 2021)). Nationwide, demand was set to the capacity of all fabs of companies headquartered in the United States, or 1.65 million 12-inch equivalent wafers per month (IC Insights, 2021). Domestic capacity was expanded to satisfy this demand for the reshoring SC scenario.

SC-RI Module 1: SC-Profiling

(1) Existing and Potential Entities and Connections

In this microchip SC, the domestically produced SEMW (SEMW_DP) begins with the chemicals (CHEM) produced by domestic chemical suppliers and raw wafers (RAWW) imported from overseas (Khan, 2021). In fabs, CHEM and RAWW are processed into SEMW_DP, which flow to the distributors and, finally, for ATP, creating the final microchip end-products. Any unsatisfied demand was assumed to be filled by imported SEMW (SEMW_IP) arriving through one or more of the 48 modeled U.S.-based ports. The microchip SC in this study, thus, consists of the direct suppliers of CHEM, direct suppliers of RAWW, fabs, ports handling the SEMW_IP, distributors, ATPPs, along with the major commodity flows, as depicted in Figure A1. The sources of data used in creating this SC materials flow representation are given in Table A1.

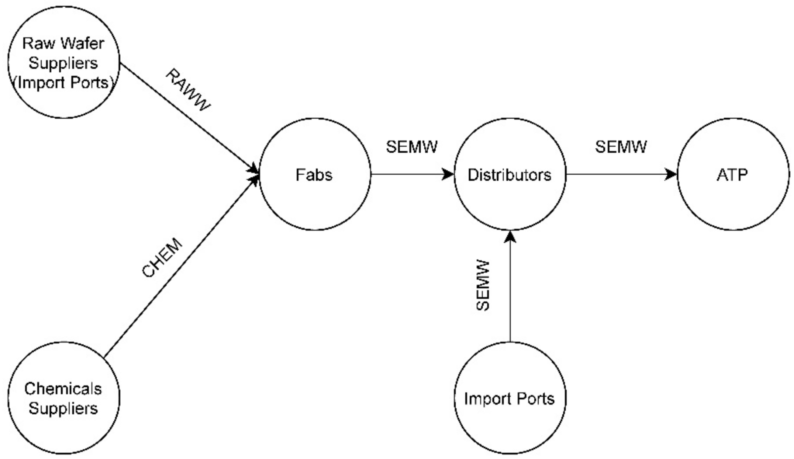


Figure A 1. General layout and material flow in microchips front-end fabrication SC network.

(2) Supply and Demand Attributes

All suppliers of raw or middle-products, except fabs, were assumed to have unlimited capacity. The capacities at the identified fabs are listed in Table A2. The demand for SMEW of each inhouse ATP (IATP) is assumed equal to the current total capacity of the fabs owned by the IATP's parent company, and the demand for the only outsourced ATP (OSAT) in the United States is assumed to be the difference between the nationwide demand and the sum of all IATP demand.

(3) Parameters for Cost Estimation

Parameters for microchip SC cost estimation are listed in Table A3.

(4) BOM

According to TSMC (2012), to produce 14 million SEMW_DP, 15.4 million RAWW, 1.6 million cubic meters of process chemicals, and 0.1 million tons of bulk chemicals are needed. Raw materials flow required for 12-inch equivalent wafer manufacturing is shown in Figure A2.

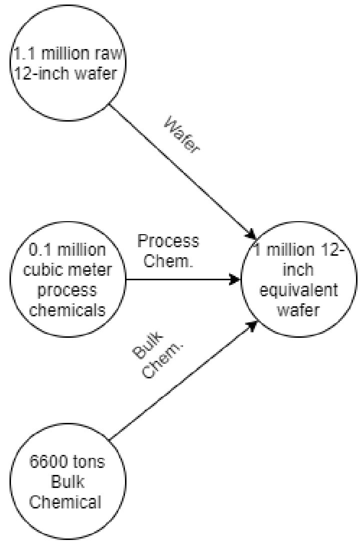


Figure A 2. Major material flow and BOM in microchips front-end fabrication of 12-inch equivalent wafer.

SC-RI 2: SC Structure and Commodity Flow Analysis

The layout (selected entities and commodity flows) of the existing microchip and post-reshoring SCs are presented in Figs. A5 and A6, respectively. Note the emphasis on expanding operations in California, New Mexico, Arizona, Texas, and portions of the Northeast. This aligns well with recent announcements for plant expansion (e.g., Wu and King (2020) and Sohn (2021)). The aggregated value of the top 10 O-D pair commodity flows (Figure A3) and top 10 inbound ((a) of Figure A4) and outbound ((b) of Figure A4) flows during the 2-year case study period are provided.

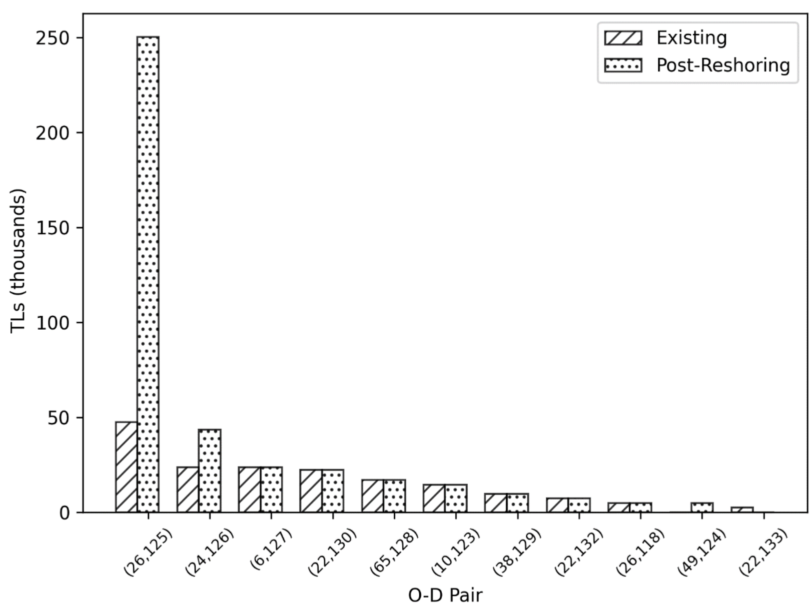
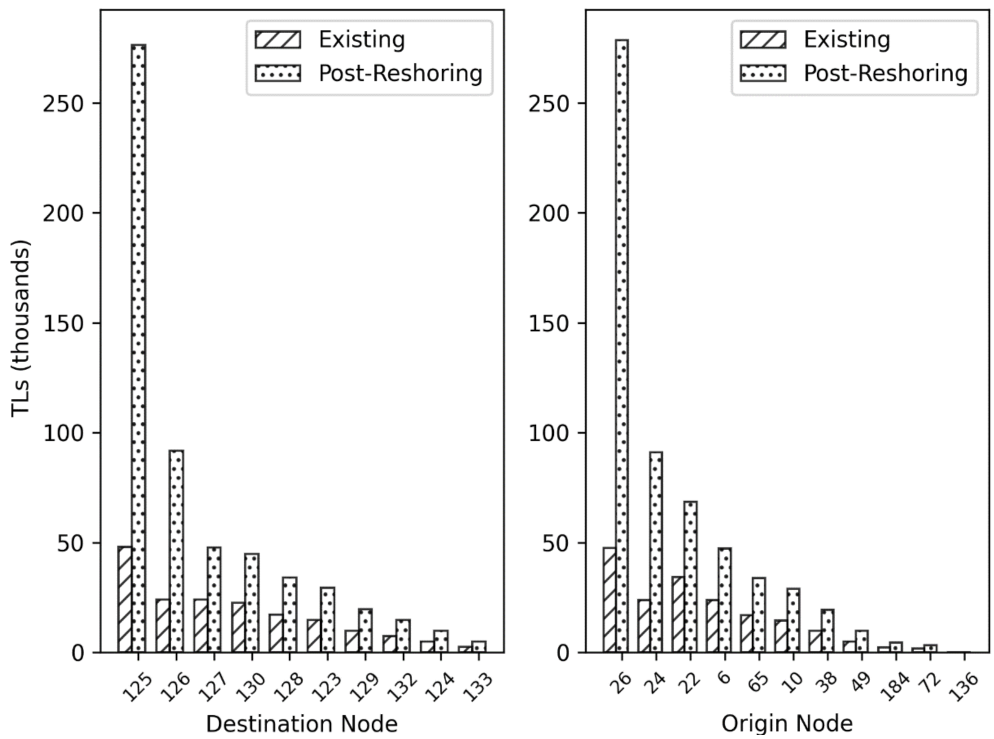


Figure A 3. Comparison of top 10 O-D pair flows in existing and post-reshoring microchip SC.



(a) (b)

Figure A 4. Comparison of top 10 inbound (a) and outbound (b) flows in existing and post-reshoring microchip SC.

SC-RI 3: Impact Analysis

Impact analyses are provided in this report. TMs and TLs of different SC segments for microchip SC are provided in Table A4.

Table A 1. Data sources for the location of entities in each echelon.

Entity Echelon	Data Source	Comments
Container ports	HIFLD database (U.S. DHS, 2020)	They are the 48 continental ports in the Major Ports file with GRAND_TOTAL value over 10 million.
Chemical suppliers	Khan(2021)	Locations for Entegris (24 locations), Emdgroup (9 locations), and Dupont (39 locations) are identified from the official website of each corresponding company.
Fabs	Platzer et al. (2020)	Plants names and locations in Table A2
ATPPs	Khan(2021)	In-house ATPPs owned by the fabs' parent company are assumed at the same locations as the fabs.

Table A 2. Capacity for the major U.S.-based fabs.

Company	Number of Fabs	Location	Current Capacity (12-inch equivalent)	Comments
TSMC	1	Phoenix, AZ	0	According to (Shilov, 2020), TSMC currently has no production in Phoenix, AZ
Samsung	0	Talyor, TX	0	According to (Sohn, 2021), these are 4 possible locations Samsung may setup new fabs.
Samsung	0	Queens_Creek, AZ	0	
Samsung	0	Genesee_County, NY	0	
Samsung	0	Goodyear, AZ	0	
GlobalFoundries	2	Malta, NY	60,000	(Encyclopedia, 2021a)
GlobalFoundries	1	East Fishkill, NY	20,000	(Moorhead, 2019)
Intel Corporation	2	Chandler, AZ	98,000	(Flaherty, 2021)
Intel Corporation	4	Hillsboro, OR	197,000	
Intel Corporation	2	Albuquerque, NM	98,000	
Micron Technology	1	Lehi, UT	70,000	(Encyclopedia, 2021b)
Micron Technology	2	Manassas, VA	40,000	(Robertson, 2003)
Samsung	2	Austin, T3X	92,000	(Encyclopedia, 2021b)
Skorpios	1	Austin, TX	10,000	
Texas Instruments	1	Richardson, TX	30,000	(Lammers, 2003)
Texas Instruments	1	Dallas, TX	10,000	

Table A 3. Cost estimation for microchip SC.

Cost Type	Cost Parameter	Parameter Value	Comments
Investment cost	Fabs fixed opening cost	$800 million	Assumed
	Other facility fixed opening cost	$240,000 per year	For a $12/year/sqft. rental price (LoopNet.com, 2021) with the industry space for a typical plant at roughly 20,000 sqft. (Schmidt, 2020)
	Fixed expansion cost for all facilities	$2 per day	Ivanov (2017)
	Fabs expansion cost (a unit of 20,000 wafers per month)	$2.72 billion	Estimated based on TSMC fab18 (capacity at 120,000 WPM) with total investment cost at $17.08 billion
	Other facilities expansion cost	$2 per day	Ivanov (2017)
Transportation cost	TL rate	$3.2/mile	(Williams, 2020)
	Truck capacity	22.7 m^3	(SafeRack's Industrial Index, 2020)
	Chemical's density	1000 kg/m^3	Most of the chemicals are fluids in normal pressure
	Wafer packaging	0.34 m*0.42 m* 0.33 m (25 unit)	(Entegris, 2020)
Procurement cost	Raw wafer and chemical	$117 per wafer	Based on material cost at $1.18 billion, with shipments at 10.1 million for year 2019 (TSMC, 2020)
Production cost	Fabs labor cost	$1776 per wafer	Based on manufacturing cost at $17.94 billion, with shipments at 10.1 million for year 2019 (TSMC, 2020)

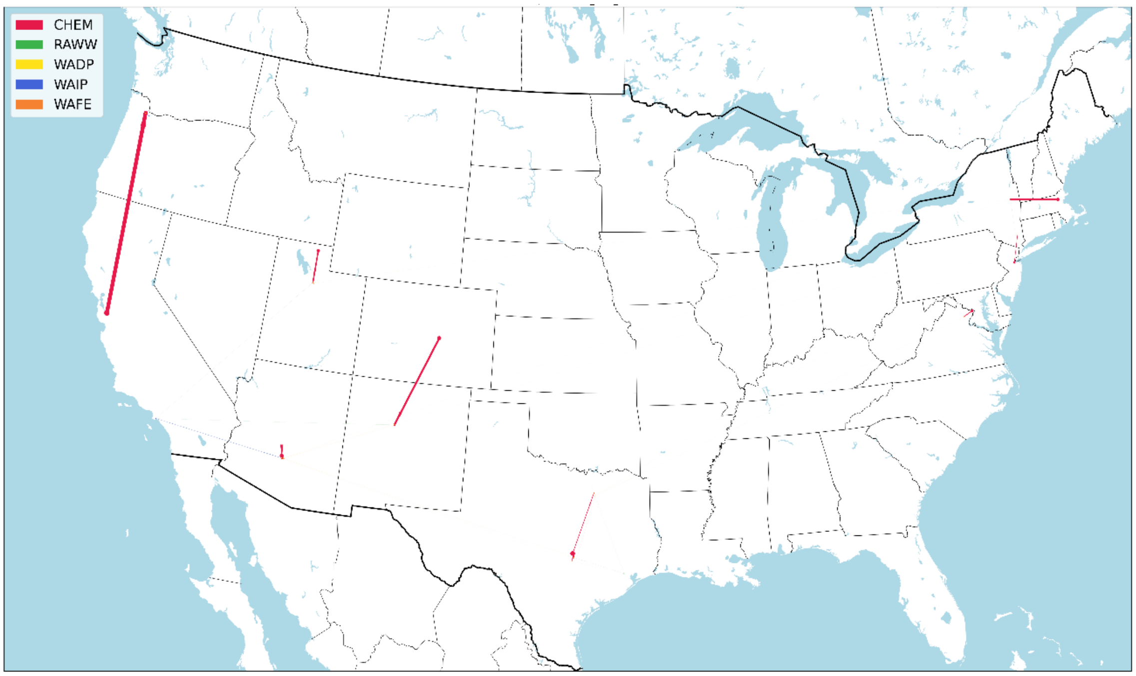


Figure A 5. Layout of existing microchip SC.

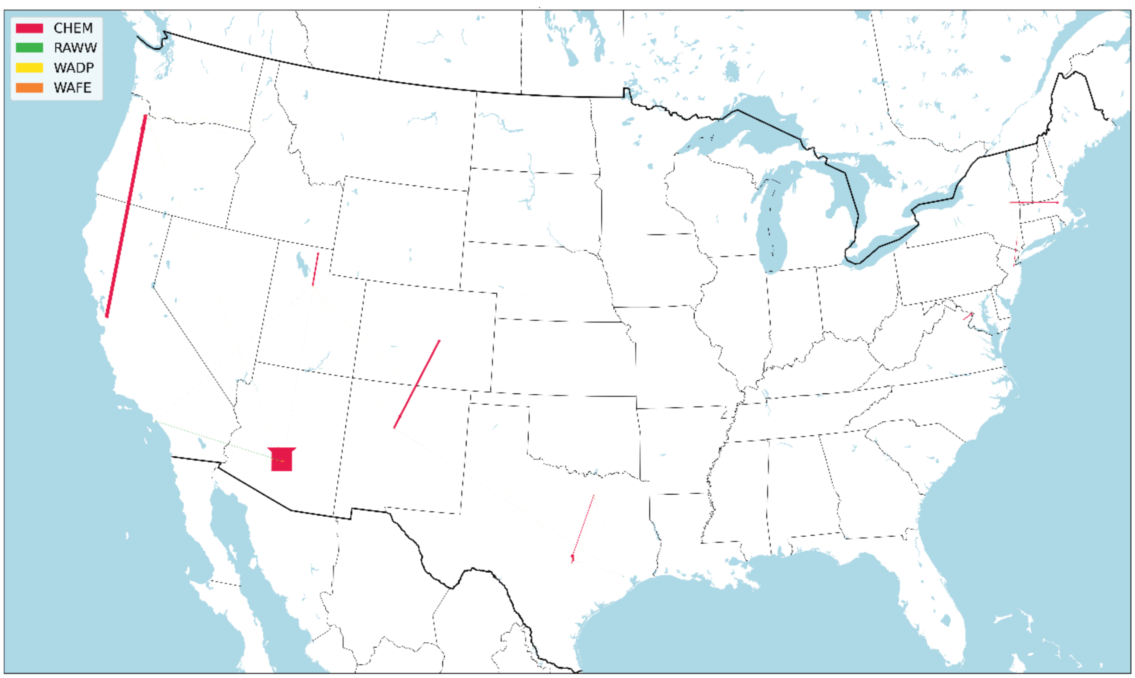


Figure A 6. Layout of post-reshoring microchip SC.

Table A 4 Comparison of TMs and TLs for microchip SC.

	TMs (Thousand)			TLs		
Commodity	**Existing**	**Post-reshoring**	**Increase**	**Existing**	**Post-reshoring**	**Increase**
CHEM	47,171	46,589	-582	174,773	402,091	227,318
RAWW	485	1,389	904	1,691	3,885	2,194
SMEW DP	780	1,160	380	1,541	3,535	1,994
SMEW IP	644	0	-644	1,995	0	-1,995
SMEW	58	58	0	3,529	3,529	0
Raw/Mid.	47,656	47,978	322	176,464	405,976	229,512
Final prod.	1,482	1,218	-264	7,065	7,064	-1
Total	49,138	49,196	58	183,529	413,040	229,511

APPENDIX B

Avoided Economic Losses and Resilience Calculation for a Microchip SC

The real price function for microchips is unavailable, and regression based on global historical sale data (Table B1) for semiconductors is used to get the unit price function (Figure B1). According to the unit price estimated in Table B1 and the domestic microchips manufacturing value in 2020 estimated as $27.3 billion (11% of $248 billion (Khan, 2021)), the existing domestic microchips manufacturing quantity is estimated to be 110 billion units, and such quantity increased to 250 billion in the reshoring scenario (25% of $248 billion (Khan, 2021)). The domestic demand in 2021 is estimated as 243 (<250) billion units, equivalent to 21% of global market (SIA, 2021a). The avoided economic loss is estimated in equation (B1).

$$\Delta c = c = \sum_{x=1}^{d_i - s_i} f(x) = \sum_{x=1}^{243-110} 0.0016x + 0.2729 = \$50.6\ billion. \qquad \text{(B1)}$$

Resilience improvement is calculated in equation (B2).

$$R = \Delta c / c = 1. \qquad \text{(B2)}$$

Table B 1. Sale data for semiconductors from 2016 to 2021 (SIA, 2020; SIA, 2021a)

Year	2016	2017	2018	2019	2020	2021
Sale ($billions)	342	400	468.8	412.3	440.4	555.9
Quantity (billions)	869	975	1,046	976	1,002	1,150
Unit price ($)	0.394	0.410	0.448	0.422	0.440	0.483
U.S. demand gap (billions)	74	96	111	96	102	133

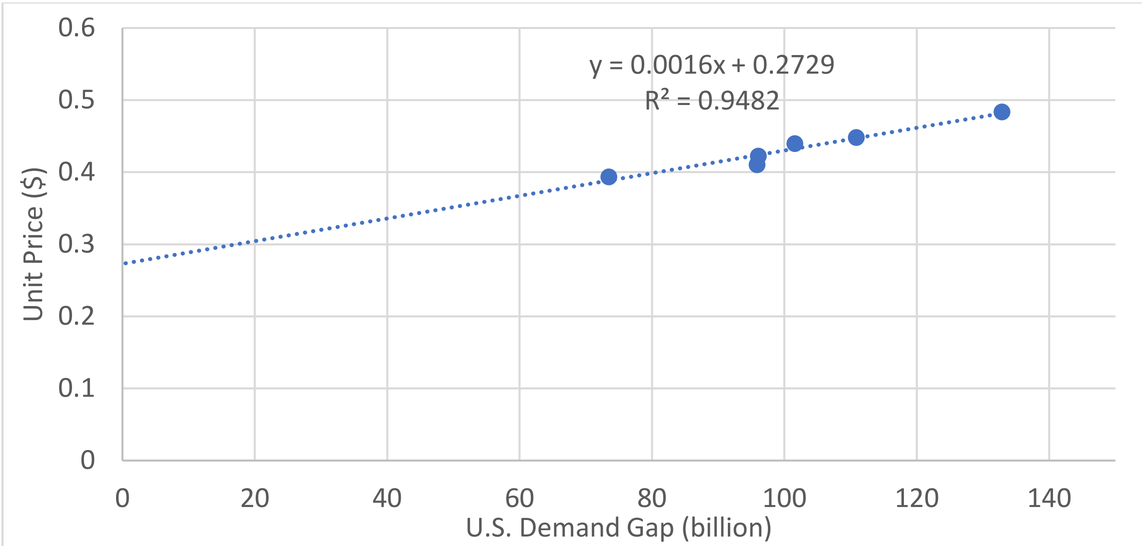


Figure B 1. Regression of unit price and demand gap of semiconductor