Stress Testing for Resilience of Semiconductor Supply Chains

Zachary A. Collier
Dept. of Management
Radford University
Radford, VA, USA
zcollier@radford.edu

Davis C. Loose
Dept. of Systems and Information Engineering
University of Virginia
Charlottesville, VA, USA
dcl6d@virginia.edu

Elvie Sellers
Dept. of Systems and Information Engineering
University of Virginia
Charlottesville, VA, USA
fam3ys@virginia.edu

Thomas L. Polmateer
Commonwealth Center for Advanced Logistics Systems
Petersburg, VA, USA
polmateer@virginia.edu

Madhur Behl
Dept. of Systems and Information Engineering
University of Virginia
Charlottesville, VA, USA
mb2kg@virginia.edu

Igor Linkov
University of Florida and US Army Engineer Research and Development Center
Concord, MA, USA
Igor.Linkov@usace.army.mil

James H. Lambert
Dept. of Systems and Information Engineering
University of Virginia
Charlottesville, VA, USA
lambert@virginia.edu

***Abstract*—The supply chains of semiconductors and integrated devices supports industry across all economic sectors. Globally, the supply chain is experiencing a variety of stressors and disruptions, with effects that cascade across the economy, causing product delays and enterprise losses. However, quantitative models that support an understanding of how stressors influence supply chain performance are needed. Here we show how stress testing can be used for assessing the impact of disruptions on supply chain performance metrics and for characterizing system resilience. We demonstrate a framework that utilizes discrete event simulation for stress testing the resilience of a semiconductor supply chain. Our results include a comparison of resilience curves with and without risk management countermeasures, showing the resilience-enhancing benefits of various supply chain management strategies such as maintaining safety stock and sourcing from multiple suppliers. Supply chain managers can utilize stress testing principles and methodologies to configure their supply chain and engage in practices that contribute to system resilience.**

Keywords—risk management, disruptions, systems engineering, performance metrics, decision making, business continuity

I. Introduction

Semiconductors are the products of a $0.5 trillion-dollar supply chain industry that is essential in further developing electronic devices, enabling advances ranging from energy and communications to computing and transportation, impacting everyday life both directly and indirectly [1]. Even as the global semiconductor supply chain is significantly growing, this comes only after the detrimental effects of the COVID-19 pandemic which upset global supply chains [2]. Existing problems were only exacerbated with geopolitical issues such as the Russia-Ukraine conflict posing new hindrances to international trade and the semiconductor supply chains [3].

To address variety of stressors of the semiconductor supply chain, it is urgent that latest principles and methods of systems analysis and risk management are implemented. Without a functioning semiconductor supply chain that is able to “bounce back” after tumultuous events and disruptions, technological innovation and larger world markets could be impacted, resulting in labor shortages and a lack of consumer goods, metals, chemicals, commodities, and even food [4].

Supply chain managers need to understand the sources of disruption of their production and distribution systems [5-6] and the ability of the system to recover. In doing so, managers are then able to devise risk mitigation plans and resilience-enhancing capabilities, developing a playbook of what steps they should be taking to ensure that their supply chains can remain resilient and viable [7]. To systematically identify current and future areas of risk and the associated strategies to take to reduce such risks when present, managers must account what steps to take in order to protect the supply chains [8]. This can be achieved through stress testing, especially stress testing that focuses on the resilience of the supply chain. Such supply chain resilience stress testing focuses on the ability of the supply chain to recover and respond to disruptions along one or more performance metrics or key performance indicators (KPIs) [9].

Through mathematical simulation in the context of a supply chain model, the capability to identify potential risks and assess resilience is made possible by focusing on how the system will respond under current or idealized configurations, and its findings can thus be applied to future implementation procedures of supply chains [10]. Discrete event simulation (DES) can model supply chain networks and demonstrate such current and/or idealized configurations, allowing managers to

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identify and understand how their system at hand can respond to present or future risks [11].

This paper develops and demonstrates a discrete event simulation-based stress test resulting in resilience curves for supply chain KPIs. As supply chains become more interconnected and exposed to more stressors, a stress testing methodology is needed to understand the resilience of supply chains under various scenarios and extreme events [12].

II. Background

A. Discrete Event Simulation

Discrete event simulation (DES) is a modeling technique used to emulate real-world systems using computational rather than physical resources. DES establishes sets of logical operations, which are executed over discrete time steps. The results of each time step are used to adjust model parameters at subsequent time steps [13]. DES models are often used in experimental analysis as the models have a high degree of precision, allowing for the management of variables and to examine how systems react to changes [14]. Fields such as transportation, healthcare, logistics, and robotics have used DES as a way to examine system dynamics *in silico* rather than by setting up complicated experiments. Supply chains are a good candidate for DES analysis, as the procurement, production, and movement of goods follow well understood rules and logic. Further, DES techniques are flexible and allow for analysis of how disruptions impact operations [15-17]. This allows for the integration and testing of mitigation techniques to reduce the harm of disruptive scenarios [11].

B. Supply Chain Resilience

Resilience has historically been described as the ability of a system, such as a supply chain, to "bounce back" after an impending event, but recent and improved definitions of resilience seek to expand this original understanding to incorporate the capacity of a system to further adapt and transform once a risk has occurred [18]. In terms of the global shortage of semiconductors further exacerbated by the COVID-19 pandemic along with other factors, resilience of such future supply chains of computer chips is imperative [7]. Two areas of resilience commonly focused on deal with inherent capabilities for a system to respond, as well as adaptive performance of a system during abnormal times [19]. Many times, increased interest in supply chain risks and resilience is usually rooted out of necessity, revealing a "lack of preparedness and insufficient recovery capabilities across numerous areas of potential conflict" once disaster has already struck [7].

Numerous studies have attempted to quantify supply chain resilience [20-23]. Many quantitative supply chain resilience methods measure a system's critical functionality over time, observing a decrement in functionality following the disruption and a gradual recovery back to pre-disruption levels of functionality. This chart is sometimes referred to as the "resilience triangle" [24] or the "disruption profile" [25].

Common to quantitative measures of supply chain resilience is the consideration of time - how quickly a supply chain can react successfully while mitigating possible sources of risk while encountered. Simchi-Levi et al. [26] defined the metric of time to survive (TTS), which was described as the maximum duration that a supply chain could function without a loss of performance after a node in the network is disrupted. In addition to the abovementioned TTR metric, these supply chain metrics provide quantitative measures of the supply chain's performance over time.

C. Stress Testing

The International Monetary Fund (IMF) described stress testing as *"...a range of techniques used to assess the vulnerability of a portfolio to major changes in the macroeconomic environment or to exceptional, but plausible events. The objective of a stress test is to make risks more transparent by estimating the potential losses..."* [27]. Stress tests are used to determine the stability of a system or entity, traditionally a financial portfolio or institution, when pushed beyond normal operational conditions [28]. The key to stress testing is the development and application of plausible stress scenarios [27,29]. The performance of the system under stress is typically compared to the performance of the system under a normal, baseline scenario [30-31]. The scenarios used to stress the system do not have to be complex, but they should be defined in such a way as to uncover points of failure [32].

Methodologically, there are several generalized steps for conducting a stress test [33]. After the scope has been defined, scenarios are generated. Data are collected to support the scenarios and modeling. Modeling is then conducted to determine the impact of the scenarios on the parameters of interest. Finally, reporting is conducted and management actions are determined [33]. The final step is important, as stress tests should be utilized as a risk management tool that informs business decisions [34].

While stress testing has been utilized extensively in the financial sector, it has been extended to other domains including critical infrastructure [35], transportation systems [36], water distribution systems [37], and healthcare systems [38]. Stress testing of supply chains has been conducted as well. Jain and Leong [10] used simulation software to model the impact of demand surges on supply chain inventory needed to satisfy demand. Ivanov and Dolgui [7] described a stress testing methodology using simulation software to produce a digital twin of the supply chain, following three steps: disruption identification, disruption modeling, and disruption impact assessment. Simchi-Levi and colleagues have developed stress testing methodologies for supply chains, defining the time to recovery (TTR) metric as the time it takes a stressed node in a supply chain network to be restored to full functionality [39-41]. The model was applied to the automotive supply chain, using it to support risk management activities that reduce the firm's risk exposure [40-41].

Linkov et al. [35, 42] distinguished between risk stress testing and resilience stress testing, following from the distinction between risk and resilience [43-44] – perfect risk management would mean that the supply chain is prepared for, and is never adversely impacted by disruptions. Resilience, on the other hand, accepts that some disruptions cannot be anticipated and therefore some performance impacts will be experienced, but the focus is placed more heavily on how the system can return its critical functionality back to pre-disruption levels [43-44]. Extending this distinction to stress testing, risk stress tests tend to focus on how a system can prepare for and absorb a shock, while a resilience stress test focuses on how a disrupted system (or system element, such as a node in a supply chain) performs in degraded conditions and subsequently recovers and adapts to new operating conditions [35, 42]. Specifically, Liknov et al. [35] proposed a three-tiered process for resilience stress testing of infrastructure, starting with a screening-level assessment, followed by a semi-quantitative assessment, and finally advanced modeling using various quantitative methodologies.

III. Methodology

Discrete event simulation is used to model an example of a subset of a semiconductor supply chain, showing how various organizations, processes, and constraints interact to produce and deliver products. The simulation is exposed to disruptive scenarios that alter the parameters of the simulation, showing how performance changes over time. These results are used to develop mitigation techniques to reduce the impact of disruptions and improve system resilience.

Figure 1 describes the discrete event simulation process of the semiconductor supply chain. There are three primary elements of the supply chain: the foundry, OSAT (outsourced semiconductor assembly and test), and system integrator. The foundry purchases raw materials from outside the simulation and converts them into a product. The OSAT purchases this product from the foundry and further refines the product. The system integrator purchases products from the OSAT, integrates them into a final product, and sells them at predefined times in the simulation. Each element of the supply chain shares several features, including a maximum inventory capacity, initial stock level, a policy for ordering new materials, manufacturing rates, delivery times, and various associated costs. Each time unit that passes, called a "tick", advances the simulation at which point a series of logical elements are investigated. This includes checking if materials need to be ordered, if products need to be delivered, and if there are work-in-progress products that need to be manufactured.

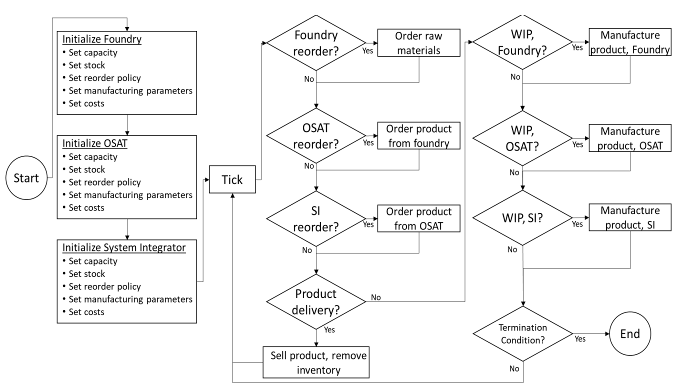

Fig. 1. Overview of the Discrete Event Simulation model of a semiconductor supply chain with three elements.

The foundry initializes several parameters. The foundry has a maximum capacity of 200 completed products and begins with an inventory of 100 completed products. The foundry will reorder raw materials when the inventory reaches 25% (50 units) of the maximum capacity. The foundry orders in batch sizes equal to 50% of the maximum inventory (100 units). Ordering raw materials incurs a cost of $1 per unit. The foundry sources products from outside of the simulation - that is, the foundry will always receive the full amount ordered. After materials are ordered, they need to be manufactured into completed products. After a 15 time-step delay between the order and the arrival of the materials, the foundry begins to manufacture finished products at a rate of 15 units per time step, with a two time-step delay between batches to simulate set-up time. Manufacturing costs for the foundry are one dollar per unit. Finished products are kept in inventory until ordered by OSAT - holding costs are incurred at each time step at a cost of $0.25 per unit on hand. If the OSAT orders more product from the foundry than there is inventory, the foundry incurs a stockout cost of $8 per unit failed to deliver.

The OSAT has a maximum capacity of 150 completed products and begins with 20 completed units in inventory. The OSAT reorder point is at 25% (38 units) of maximum capacity, reordering in batches equal to 50% of the maximum capacity (75 units). Products have an ordering cost $0.50 per unit ordered. Products take three time steps to arrive between order and delivery. Ordering products from the foundry costs $2 per unit. If the OSAT orders more product from the foundry than there is inventory, the OSAT receives however much product is available at the time. The OSAT will begin to manufacture products at a rate of five units per time step with a two time step setup. Manufacturing costs for the OSAT are $1 per unit. Finished products are held in inventory, incurring a holding cost of $0.15 per unit per time step. If the system integrator orders more product from the OSAT than available inventory, all product is sent and a stockout cost of $3 dollars per unit not delivered is incurred.

The system integrator (SI) has an initial capacity of 100 units and initial inventory on hand of 20 products. The system integrator is given a user-defined parameter consisting of product delivery dates and amounts - in this case deliveries are due at times 66, 132, and 198. 60 units are sold at each of these three times. Because delivery dates are known, the SI can work backwards to identify when and in what quantities products must be ordered from the OSAT in order to meet demand. The SI orders products at a cost of $0.50 per unit. The SI will order only enough product to meet demand on time. If the OSAT does not have enough product on hand, the SI will order the entire inventory. There is a five time step delivery time between placing an order and the materials arriving at the SI. Products are manufactured at a rate of seven products per time step with a two time step set up between manufacturing batches. Manufacturing costs for the SI are equal to $1 per unit. Finished products are held in inventory until the delivery time at a holding cost of $0.15 dollars per unit. If the SI fails to meet a full order size, it will deliver all product on hand and incur a stockout cost of $8 per unit that is not delivered.

The simulation is then used to test the impacts of various disruptions. Disruptions may include natural disasters, cyberattacks, climate change, labor disputes, or combinations of these factors. Disruptions may occur on one or multiple segments of the supply chain. The following section explores the results of this analysis, examining how the supply chain reacts to and recovers from these disruptions, offering potential mitigation strategies for reducing the harms of disruption.

IV. Results

Results show how disruptions impact system performance in terms of costs incurred. The resilience curves presented in this section show the results of three simulations - the baseline simulation, a simulation with disrupted performance, and a simulation with disrupted performance but including various mitigation techniques. The baseline simulation is represented by a horizontal line at 0, with the two disrupted scenarios showing the difference in costs incurred at each time step. Costs are represented in terms of negative difference in cash flow to emphasize the decrease in performance.

Figure 2 describes the results of the baseline simulation without any stressors, showing the inventory and costs over time for all three elements of the supply chain during a 200 time step simulation. Due to the initial constraints, the system integrator is unable to meet the 60 unit delivery at time 66, selling only 50 units. The cost over time graph for the system integrator shows the penalty for this stockout, inducing a cost of $80 for failing to meet the delivery. The system integrator is able to order enough product from the OSAT for subsequent deliveries. The OSAT delivers all available products at the first time step, and in fact has a short period of negative stock. The OSAT pays a stockout penalty for failing to deliver the full order. The foundry is able to meet demand for the entirety of the simulation. This describes the baseline scenario for the discrete event simulation.

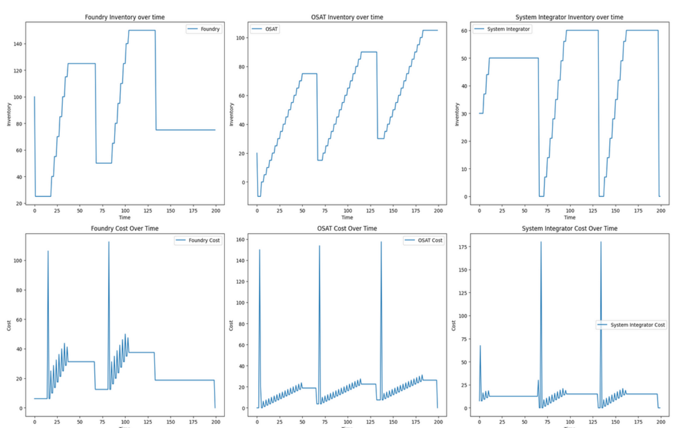

Fig. 2. Overview of the performance of the discrete event simulation for a semiconductor supply chain in the baseline scenario

Figure 3 describes the impacts of disruptions to the OSAT level on the system integrator. The blue line shows the baseline performance without disruption. The orange line describes performance given a disruptive scenario. In this case, an event such as a natural disaster, drought, pandemic, or labor dispute prevents the OSAT from delivering products to the system integrator in a timely manner. Specifically, a disruption occurs at system time 38, at which point the lead time between the placement of orders and the delivery is increased from three to 100. This delay does not allow enough time for the system integrator to manufacture a complete order of 60 units due at time 198. The graph shows the reduction in performance due to disruption at time 130. Over time, the system integrator begins to recover and return to normal levels of performance. Contrast this with the green line, showing the same disrupted scenario but with the added mitigation of 20 units of safety stock. Note that the mitigated system integrator immediately has worse performance than the baseline as more product is ordered, manufactured, and kept on hand. However, the mitigated simulation resists the severe effects of the delayed delivery, as it is able to completely fulfill the final order. However, the overall cost of keeping safety stock on hand is greater than the baseline scenario due to holding costs.

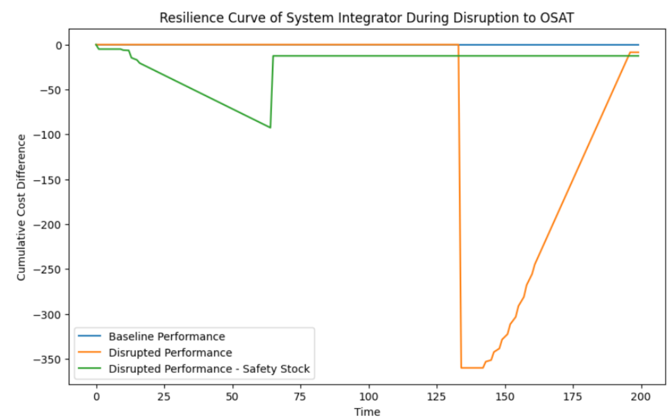

Fig. 3. Resilience curve of the performance of the system integrator in the baseline, disrupted, and mitigated scenarios. Performance is measured by the additional cash flow over the baseline due to disruption.

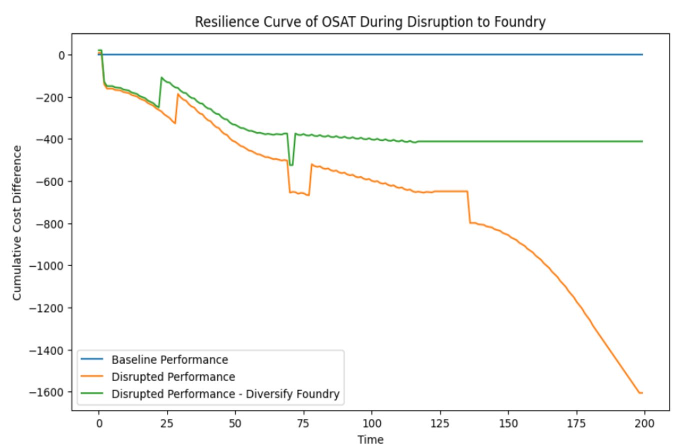

Fig. 4. Resilience curve of the performance of the OSAT in the baseline, disrupted, and mitigated scenarios. Performance is measured by the additional cash flow over the baseline due to disruption.

Figure 4 describes the impacts of disruptions to the foundry on the OSAT. That is, the OSAT experiences disruption due to the cascading effects from earlier in the supply chain. The blue line shows the performance of the OSAT in the baseline, non-disrupted scenario. The orange line shows the degradation of performance over time due to disruption. In this scenario, the foundry has experienced a delay in production beginning at time step zero, which prevents the OSAT from receiving a full order. As such, the OSAT begins the simulation behind schedule and never returns to baseline performance, continuing to incur additional costs from increased holding costs and stockout costs. The green line represents the same disruptive scenario but with the added mitigation of diversified sourcing from foundries. That is, the OSAT orders materials from two foundries such that if one is disrupted, the second foundry remains in baseline performance. The OSAT orders half of its product from each of the two foundries. As shown by the green line, performance degrades initially but at a reduced rate, and eventually stabilizes rather than degrading further. In both disrupted scenarios, the OSAT is never able to fully recover to the baseline performance level, but the total impact can be reduced. In a real-world semiconductor supply chain, the better performance during disruption provides additional opportunities for the organization to restore performance.

V. Discussion and Conclusions

This work presents a method for exploring the impacts of disruptions and mitigation techniques toward resilient supply chains. We developed and demonstrated a discrete event simulation model of a semiconductor supply chain with three elements: the foundry, OSAT, and system integrator. The DES demonstrates how inventory and costs change over time and presents a testbed for examining the impact of disruptions. Two types of disruption were tested - a delay in delivery times due to disruptions in the OSAT, and a reduction in delivery quantity due to disruptions in the foundry. Both scenarios show how additional costs are incurred due to disruption. Potential mitigation techniques were applied to these scenarios. When the OSAT has delays in delivery times, the system integrator is instructed to keep safety stock on hand. The system integrator was able to avoid the major disruption of a stockout using the safety stock, reducing the total cost of disruption. When there were disruptions to the foundry preventing the delivery of full orders to the OSAT, the performance of the OSAT degraded and was not able to recover. However, in the same scenario, but with the OSAT ordering from two foundries, one disrupted and one not, the OSAT is able to reduce the total impact of disruption.

The demonstrated methodology differs from other resilience stress testing methodologies, such as the three-tiered approach proposed by Linkov et al. [35]. Specifically, we do not include the first two tiers (screening and semi-quantitative) into our approach. However, the discrete event simulation model described here could fit into the third tier of advanced modeling proposed by Linkov et al. [35].

The limitations of the study are as follows. First, the values used to parameterize the model are illustrative. Additionally, while the semiconductor supply chain is complex to map and involves multiple actors [45], we focused only on a subset of the larger supply chain. However, the illustration provides a proof of concept of the methodology and a platform for further refinement. Future work includes building a larger network of supply chain nodes and further parameterization of economic performance metrics [46], as well as integrating relevant supply chain stressors into a dynamic risk register [47].

The findings show that supply chains that are subjected to disruptions potentially face impacts in the form of degraded performance (e.g., higher costs, schedule delays). However, there are ways that supply chains can be designed in a more resilient way, including increasing redundancy, building in flexibility, and cultural change [48]. Increasing capacity, visibility/traceability, and supply chain security can also help to reduce risk and increase resilience [49-50]. Enhancing trust between buyers and suppliers within the supply chain can also reduce risks [51]. However, it is important to note that such measures may not always be enough to restore supply chain performance to a pre-disruption level. Sometimes the system enters into a new, degraded state, as shown in Figure 4. This new state, while less preferable, may itself be resilient in the sense that performance will “bounce back” to this degraded state [52].

In conclusion, the semiconductor supply chain is crucial for the global economy and therefore should be made resilient to disruptions and extreme events that may impact supply. Understanding how stressors influence the supply chain’s performance, and investigating its tendency to recover and adapt (or not) to these stressors, is necessary to ensure the health and vitality of the supply chain and the industries that it serves.

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