Complex Economic Consequence Analysis to Protect the Maritime Infrastructure

Dennis Egan
Rutgers University
CCICADA
Piscataway, NJ, USA
deegan@dimacs.rutgers.edu

Christie Nelson
Rutgers University
CCICADA
Piscataway, NJ, USA
cnelson@dimacs.rutgers.edu

Fred Roberts
Rutgers University
CCICADA
Piscataway, NJ, USA
froberts@dimacs.rutgers.edu

Adam Rose
University of Southern California
CREATE
Los Angeles, CA, USA
adamzros@usc.edu

Andrew Tucci
Rutgers University CCICADA
Piscataway, NJ, USA
andrew.e.tucci42@gmail.com

Ryan Whytlaw
Rutgers University
CCICADA
Piscataway, NJ, USA
rwhytlaw@gmail.com

***Abstract*— The marine transportation system (MTS) is a critical part of the nation's supply chain. Malicious actors, natural disasters, pandemics, geo-political events and larger marine casualties such as the 2021 Suez Canal grounding incident can disrupt the MTS and domestic and global supply chains. To date, most research and contingency planning has focused on single-event disruptions such as oil spills or security issues. While supply chains may be resilient enough to cope with a wide variety of single disruptions, aggregated challenges may result in cascading failures. There has been little analysis of the impacts of multiple disruptions that build on each other in complex ways. This suggests that modeling the impact of multiple vector disruptions on multiple MTS targets can help policy makers, business leaders, and others anticipate, plan for, mitigate, and rapidly recover from future complex disruptions. This paper describes an approach to research questions like: What are plausible examples of complex, multi-vector disruptions to the MTS? What could make their outcomes more complicated and challenging than those of single disruptions? What are their consequences for different components of the MTS? What are some pre-disruption mitigations and post-disruption resilience tactics that might be useful in such cases? How can we estimate the time to implement them, the costs of implementation, and the reduction of impact of such measures? The project described is developing a framework to address such questions. The framework will be used to analyze the impact of different combinations of individual disruptions, including natural disasters and climate change; security events, including cyber, accidents and marine casualties; and social/political disruptions. The analysis will focus on the total economic consequences of these threat combinations and transition into a user-friendly decision-support tool to improve risk management.**

Keywords—maritime, supply chain, disruptions, economic consequences, mitigation, resilience

I. Introduction

When the container ship Ever Given ran aground in the Suez Canal on March 23, 2021, the incident caused significant supply-chain issues. Although the incident was resolved in six days, it exacerbated port congestion and container shortages. It also led to spikes in freight and energy prices, impacting manufacturing. When the Suez Canal incident occurred, the global supply chain, dominated by maritime traffic, was already impacted by the COVID-19 pandemic. How did that make the impacts of the incident worse? This question is the motivation for studying the impacts of complex, multi-vector disruptions of the marine transportation system (MTS).

The MTS is a vital part of the nation's supply chain. Malicious actors, natural disasters, pandemics, geo-political events and marine casualties such as the Suez event can disrupt domestic and global supply chains. These and other disruptions can occur singly or in combination. While supply chains may be resilient enough to cope with a wide variety of single disruptions, aggregated challenges may result in cascading failures causing unexpected and non-linear impacts. To date, most research and contingency planning has focused on single-event disruptions such as oil spills, natural disasters, or security incidents. There has been little analysis of the cascading impacts of multiple disruptions that build on each other in complex ways. We call them "complex, multi-vector disruptions" and our project aims to identify examples of that will help identify what might make such a disruption most particularly threatening. This suggests that modeling the impact of multiple vector disruptions on multiple MTS targets can help policy makers, business leaders, and others anticipate, plan for, mitigate, and rapidly recover from future complex disruptions. This is especially important as U.S. Coast Guard (USCG) and U.S. Department of Homeland Security (DHS) leadership seek to manage risks to an MTS increasingly reliant on complex technology and skilled labor. Accordingly, we ask: How do multiple, interconnecting disruptions of the MTS produce outcomes that are much more complicated and challenging than those of single disruptions, and how can we best address them? Our project is led by two DHS university centers of excellence, CCICADA led by Rutgers University (https://ccicada.org) and CREATE led by

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University of Southern California (https://create.usc.edu), under the auspices of a third, CAOE led by Arizona State University (https://caoe.asu.edu). The project is developing a framework to estimate the consequences of multiple, complex disruptions to the MTS. The framework will be used to analyze the likely impact of different combinations of individual disruptions, including natural disasters and climate change, security events, including cyber, accidents and marine casualties, and social/political disruptions. The analysis will focus on the total economic consequences of these threat combinations and transition into a user-friendly decision-support tool to improve risk management at the local, regional, national, and global levels.

II. LITERATURE

There is a good body of literature on the economic cost of disruptions to the MTS. However, typically, such studies concentrate on single disruptions, primarily to ports (see the survey on economic/cost impacts of MTS disruptions by Wendler-Bosco and Nicholson, 2019). Thekdi and Santos (2016) used scenario-based methods to measure economic sensitivity to single sudden-onset disruptions at ports. Craighead et al. (2007) studied the severity of different supply-chain disruptions. Loh and Van Thai (2015) described the cost consequences of a port-related supply chain disruption. Rose and Wei (2013), Rose et al. (2018), Wei et al. (2020) and Wei et al. (2021) developed supply chain disruption models to estimate the economic impact of various threats on the operation of ports and their direct and indirect customers. Many other studies have estimated the direct and indirect impacts of port disruptions using a broad set of economic impact models (e.g., input-output models, computable general equilibrium (CGE) models, mathematical programming tools, and econometric approaches) and found them to be sizeable (CBO, 2006; Park, 2008; Pant et al., 2013; Zhang and Lam, 2015).

There is also some literature on the potential economic impact of countermeasures developed to reduce risk to MTS systems. For example, Martagan et al. (2009) discussed rerouting of vessels; Campo et al. (2012) discussed alternatives for offloading goods to rail transportation or shore-side barges in the case of disruptions to inland waterways; Jackson (2008) studied economic savings of advanced notice of expected flooding. Chopra and Sodhi (2004) and Kleindorfer and Saad (2005) studied how to manage disruption risks in supply chains.

Port authorities and operators can implement various measures to speed up the resumption of activities and reduce ship congestion by using excess capacities of undamaged terminals or re-routing ships. Businesses affected by import or export disruptions can initiate a broad range of coping activities, such as the use of inventories, conservation, input substitution, diversion of exports for import use, and production rescheduling. However, other than the research team at the CREATE Center (cf. Akakura et al., 2015), very few of the studies have adequately factored in all the possible forms of resilience that could mute these losses by efficiently using remaining resources or by recovering more rapidly. For example, Rose and Wei (2013) included resilience tactics to estimate the economic impact across the supply chain. These tactics, such as ship re-routing, export diversion, and import substitution, reduced impacts to regional gross output by 70% in a model of a 90-day disruption to Ports of Beaumont and Port Arthur, Texas. It is worth noting that while resilience tactics have had significant success, the U.S. and other economies continue to suffer significant supply-chain disruptions. As observed in USCG (2018), "Any significant disruption to the MTS, whether man-made or natural, has the potential to cause cascading and devastating impact to our domestic and global supply chain and, consequently, America's economy and national security." USCG Sector San Francisco (2019) and USCG Sector Sault Sainte Marie (n.d.) discuss such potential cascading effects, but only for a single local MTS disruption.

III. EXAMPLE COMPLEX DISRUPTION SCENARIOS AND QUESTIONS ABOUT THEM

Our work has included interviews with various MTS experts from government, academia, and industry. Based on those interviews and research, we began to develop disruption scenarios for more detailed analysis. Each scenario includes one or more "background conditions" that are understood as supply-chain friction that does not, alone, lead to cascading impacts. This is followed by significant initial and secondary disruptions. Finally, we include additional considerations that may impact resilience, add urgency to the recovery, or otherwise influence the scenario. Our interviews, literature review, and observations of current supply-chain issues have validated this basic approach and the preliminary examples of complex supply chain disruptions described below:

Scenario 1: Vessel Fire (initial); Cyber Attack (secondary)

<u>Background Condition</u>: Surge in port activity coincides with a shortage of trucks, chassis, warehouse space, and some road and bridge repairs. The result is long lines at container terminals and greater than normal congestion. These conditions add 5-10% to cost and are essentially "below the radar" for the USCG and other agencies.

<u>Initial Disruption</u>: A fire breaks out on a vessel in the Kill van Kull (KVK) in New York Harbor. There are no deaths, but the fire takes four days to fully extinguish, blocking the channel for that time period. Overhaul, salvage, and cargo transfer takes an additional week, with much of the cargo and other vessels diverted to other nearby terminals and one-way traffic rules implemented on the KVK.

<u>Secondary Disruption</u>: A cyber-attack corrupts the data at a number of port terminals. This stops cargo operations at two terminals for 3 days. Other terminals have to slow their cargo operations by 50% for two days, while both internal IT personnel and law enforcement agencies check systems to ensure the data they depend upon are safe to use.

<u>Additional considerations</u>: The source of the fire might have been illegal or improperly stored hazardous materials in containers, or sabotage. Uncertainty about what is in any given

(now fire-damaged) container, compounded by data integrity questions, will complicate the response. Large amounts of heavy black smoke in the middle of a densely populated area raises public health concerns and longshore workers may refuse to work until air monitoring deems it safe. Various cargo owners may decide to sue each other or the vessel owner.

Scenario 2: Hurricane (initial); Credible Terrorist Threat (secondary)

Background Condition: The Russian invasion of Ukraine and associated sanctions has created a high demand for grain and LNG from the U.S. There is considerable political pressure to meet demand. High prices and pressure create an incentive for port and vessel operators to work long hours and cut corners. High water along much of the lower Mississippi has already complicated grain deliveries to New Orleans and the Gulf.

Initial Disruption: A CAT 2 hurricane impacts New Orleans and the surrounding area. The storm is accompanied with heavy rain and storm surge, causing extensive flooding and making navigation difficult. Several ships and barges that should have taken precautions waited too long and are now damaged or grounded. Several oil spills occur, each large enough to require 4-6 days of sustained cleanup.

Secondary Disruption: Credible terrorist threats and reports of suspicious activity are received by law enforcement agencies. In particular, there is a credible threat at the LNG terminal in Sabine Pass. The threats may come from Russian backed organizations, or third parties unhappy with the U.S. sanctions. Regardless, law enforcement agencies converge in the area.

Additional considerations: Conducting oil spill response operations during heightened security and law enforcement operations would also be difficult as spill contractors would have to access the waterfront. Resolving the operational challenges would further delay MTS activity, with the economic consequences falling heavily on Europe (destination for LNG), and Mideast or African nations for the grain.

Scenario 3: Wildfires and Power Loss (initial), Sustained Security Requirements (secondary)

Background Condition: A labor/management dispute between the ILWU and terminal operators has led to slowdowns and lockouts, resulting in many container ships at anchor with delays as long as 26 days, and congestion on the waterfront. Ocean shipping spot rates almost triple per container.

Initial Disruption: Wildfires damage transmission lines and substations servicing the port area in Los Angeles/Long Beach (LA/LB), leading to 3 days of blackouts/brownouts in the port area; 2 more days for full power to be restored.

Secondary Disruption: Two days after power is restored, a bomb explodes in a container at Port of LA/LB, damaging cranes. Threats of further explosions leading the Coast Guard to raise Maritime Security levels to "MARSEC 2" for the port area for all West Coast ports for one week. Workers are reluctant to work until safety is assured. Debris clearing takes 3 days, but replacing cranes much longer.

Additional considerations: MARSEC 2 would normally imply actions such as reducing the available workforce (to reduce risk), adding additional security checks on vessels and systems, and generally slowing things down to reduce churn and confusion. Cascading economic impacts would be felt across the country, because West Coast ports, especially LA/LB handle cargo that goes across most of the country.

As a key part of our research, our project seeks to understand the trajectory over time as such complex disruptions evolve, to identify their impact on different components of the MTS, and to estimate their potential economic impacts. It also seeks to identify potential pre-disruption mitigations and post-disruption resilience tactics, both short-term and long-term, and to study the length of time to implement them, the costs of implementation, and their relative reduction of economic impact. To do so, we are asking subject matter experts to give preliminary answers to such questions and are developing a technical tool to address these kinds of questions in a quantitative way. We describe such a tool in the next section.

IV. E-CAT AND MCAT

Our project is an extension of the successful "reduced form" approach to transforming sophisticated complexity models into accessible decision-support tools in the development of CREATE's Economic Consequence Analysis Tool, or E-CAT (Rose et al., 2007; Prager et al., 2018); and its extension to GRAD E-CAT by Dixon et al. (2018) and NCAT by Dixon and Rose (2021) to the nuclear threat arena.

E-CAT is an operational decision-support tool that computes the direct and indirect economic impacts of a broad range of threats but has only limited applicability to maritime threats. Its methodology is being modified to develop a tool for the accurate estimation of a broad range of port/supply-chain disruptions, including the interconnected impacts of multiple events and targets.

Unlike the E-CAT modules that are only intended to provide ballpark estimates, the tool we are developing will be able to provide accurate estimates based on a variety of threats and responses since it will be based on more extensive sets of data and more intensive stakeholder input. It will also be especially well-suited to addressing supply chain issues. The model will take into account uncertainties, thereby providing confidence intervals over a range of estimates. The enhanced software system will be referred to as Complex Maritime Economic Consequence Analysis Tool, or *MCAT.* Like E-CAT, MCAT is a decision-support tool that can provide rapid estimates of the economic impacts of extreme events in a consistent manner across multiple threats. This can provide policy-makers valuable information on resource allocation to minimize risk across threats. It can also be used to identify a need for financial assistance at early states of the recovery process. MCAT will broaden the number of threats that can be evaluated by including compounding and cascading ones.

The heart of the E-CAT approach is a computable general equilibrium (CGE) model. This is an economy-wide modeling approach that essentially characterizes the economy as a set of interrelated supply chains. It captures the workings of markets and the behavioral responses of producers and consumers to price changes, regulatory adjustments, and external shocks. It is especially adept at estimating the indirect, or general equilibrium, impacts of a disaster, or compound disasters, across sectors, socioeconomic groups, and regions.

MCAT will be an improvement over previous research by use of an internationally linked computable general equilibrium model consisting of 141 countries with 65 sectors each. The well-known Global Trade Analysis Project (GTAP) CGE model (GTAP, 2022) and related models have been successfully applied by CREATE researchers in several studies, most notably in terms of the U.S. and international impacts of international trade policy (e.g., Wei et al. 2019), port disruptions (e.g., Wei et al., 2021), and the COVID-19 pandemic (e.g., Walmsley et al., 2021).

A schematic of the components and operation of MCAT is presented in Figure 1. Early stages of the system depend on defining the Maritime Context, specifying Threats, and identifying special Roles, such as that of Cyber capabilities. This, combined with data from such sources as CART, can be used to characterize specific incidents or disruptions. Incident Features, together with an Enumeration Table (Checklist) of types of impacts and special roles functions (e.g., cyber), provide the specification of Direct Economic Consequences. Specification of Supply Chains in relation to the CGE model, together with Resilience considerations are at the core of the General Equilibrium Analysis, which computes the Total Economic Consequences.

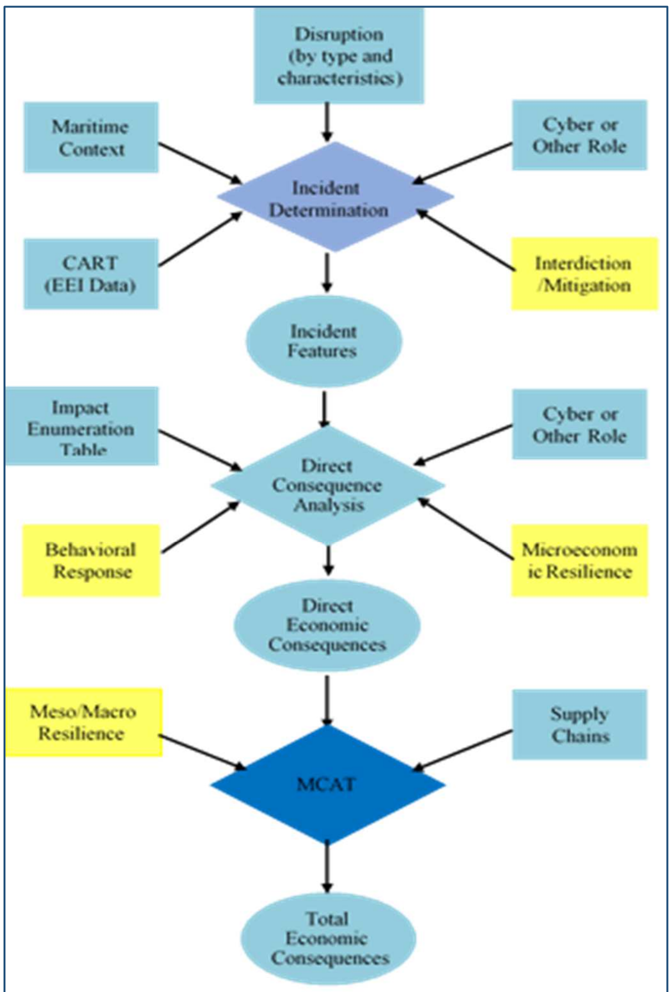

Figure 1 Operation of the MCAT Modeling System

The MCAT model will enable us to examine the international supply-chain linkages that affect the economic impacts of complex disruptions and provide insight into how to minimize them. The analytical approach uses data points on individual and compound events. It uses historical data in a simulation modeling approach to fill in many of the gaps. MCAT addresses compound disruptions and will be much more detailed in its causal linkages than E-CAT, and will involve superior data to greatly increase its accuracy. Production/operation input parameters and output metrics will be developed with input from USCG members and representatives from government agencies and the private sector to ensure that they are operationally relevant. Simulation results from MCAT will be compared to previous simulation results for similar events modeled in E-CAT.

The simulation modeling will include a range of disruptions and impacts. It will also include a broad set of mitigation and resilience tactics specific to the Maritime domain, such as ship-rerouting cargo prioritization (Wei et al., 2020), in addition to mitigation and resilience tactics used by downstream supply-chain customers, such as accessing inventories, conserving on critical inputs, substituting inputs and rescheduling production (Rose 2017). The intent of this effort is to more closely model actual MTS operations and that of its customers, and to better reflect how disruptions echo through the supply chain. Modeling how these complex interactions might likely play out and describing them in a way to feed into the new MCAT tool will require significant detail.

We are building on E-CAT's sophisticated validation methodology, which will be further enhanced and applied here. This includes providing a distribution of potential consequences, as well as confidence intervals for each disruption event. Moreover, the software will generate a time-path of impacts. To prepare the MCAT decision-support tool, we will run 500 to 5000 CGE model simulations varying key parameters for various disruption, damage, mitigation, and resilience combinations (establishment of the synthetic data base and the basis for the uncertainty analysis). We will perform regression analyses on the synthetic data (the essence of the reduced form approach), insert the regression equations into the decision-support software tool in Visual Basic, and incorporate uncertainty bounds into the software.

V. CONCLUSION

The project and, in particular its MCAT tool, is intended to help high-level decision-makers in the MTS domain assess the severity of various threats in real-time and make evidence-based decisions. It is intended to serve as a valuable tool for risk-benefit analysis, as the benefits of reducing threats are essentially the averted negative consequences. The project is intended to reveal qualitative and quantitative differences in preparedness, response, and MTS recovery activities that existing models and policies overlook. The tool's robust economic consequence modeling will incorporate input from a broad range of stakeholders that should be included in planning and post-incident decision-making. Response to complex disruptions will likely require a greater scope of authorities and capabilities than other events, and the project's results and tool will provide a way to bring the needed agencies and organizations into the process and help them plan for complex disruptions. The MCAT decision-support tool should be a valuable asset for resource and disaster planning and will permit data-driven decisions balancing threat interdiction, resource allocation, and recovery planning for the marine transportation system.

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