Resilient Supply and Demand Networks Virtual Panel

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Abstract—The DARPA Reslient Supply-and-Demand Network (RSDN) program intends to expose and mitigate sources of surprise in these networks through granular maps of these networks; augmented with risk, resilience and various relationships; analytics for data gaps and fragilities; and techniques for stress-testing in response to shocks and feedback. Challenges include incomplete, highly-fragmented data; techniques to impute missing data; simulation of network response to scenarios; and a simple workflow useful for analysts in real-world uses. In addition to DARPA, eight teams are working on solutions to these challenges; including data collection and extraction from public and licensed sources; assembling networks, including flagging data gaps and imputing relationships; network metrics for fragility and resilience; scenario analysis ranging from agent-based models to computable general equilibrium models, to real-world shock and resilience via surveys; and visual analytics to assess impact, changes and alternatives across scenarios. A panel discussion will provide each team to provide a five minute lightning overview of their research contribution, and a general question and answer session with attendees.

Index Terms—Supply chain models, Supply chain shocks, Network analytics, Network visual analytics, Network resilience models

1 Introduction

Supply and demand networks (SDNs) are extensive global relationships across private-sector vendors which provide critical goods and their precursor components and materials. These networks are suspect to disruptions both intentional (e.g. mergers, tariffs) and unintentional (e.g. natural disasters). These disruptions can cause strategic surprise and expose unpreparedness, due in part to a) imperfect knowledge of the network structure and dynamics; b) difficultly predicting different kinds of shocks from a large space of potential threats and vulnerabilities; and c) difficulty predicting changes in the network due to endogenous behavioral shifts which can be rapidly amplified through feedback effects.

The DARPA Resilient Supply-and-Demand Network (RSDN) program seeks to expose and mitigate these sources of surprise including: a) granular maps of SDNs identifying providers and their systemic relationships; b) augmentation of network maps with features such as risk, resilience and procurement relationships; c) a broad set of analytical tools for example, for identifying and working around data gaps or for exploring fragilities; and d) techniques for stress testing SDNs by specifying and simulating their responses to exogenous shocks and endogenous feedback [1]. In terms of phase-scope-goal space of SDN governance, the RSDN program uniquely focuses on *strategic* (system-level) *resilience* at the *acquisition* phase, as per Figure 1.

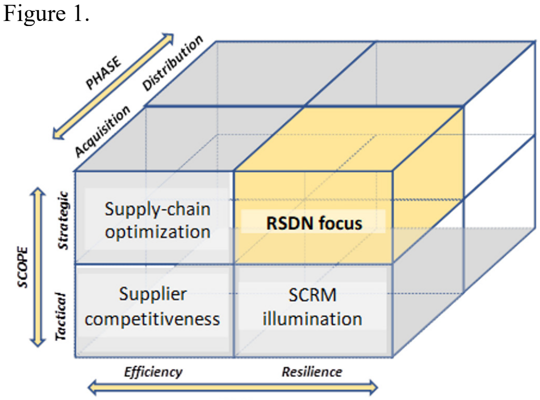

Fig. 1. RSDN focuses on *strategic resilience* at the *acquisition* phase.

A central challenge is to extract reliable signals from messy, diverse, incomplete data. To achieve this, the program focuses on three technical areas: 1) data curation and reconciliation; 2) SDN augmentation (e.g. of missing data) and analysis (e.g. systemic vulnerabilities); 3) SDN stress testing and fragility mitigation simulation.

This program, currently one year into its planned four-year duration, is still evolving and has partial results. The contribution is a panel discussion involving eight teams (plus DARPA) participating in the program. The panel will address several issues:

- There are no comprehensive datasets of granular data (i.e. global data at facility-level or company-level). What challenges have the teams come up against (e.g. scale, disambiguation) and what are their current approaches to create these global SDNs for any commodity?
- Given an incomplete SDN, what approaches can indicate blind spots, data gaps, and imputation of missing data; what approaches can find and assess areas of network weakness; and facilitate comparison between networks?
- How can one simulate recovery when there are myriad possible reactions by independent agents, and how does one understand which paths may be more likely?
- How can the above challenges come together into a simple workflow for an analyst to address the many kinds of questions arising in real-world use?

2 Background

Supply chain failures during the COVID-19 pandemic and thereafter have highlighted the need for improved understanding and analysis of supply chain relationships and resilience. Conceptualizing supply chains as supply-demand networks, where nodes represent entities and relationships represent transactions, better captures the increasingly globalized, more complex and multi-directional nature of supply chain relationships [2]. However, SDNs remain vulnerable to a wide range of disruptions, in response to which they exhibit unpredictable and emergent behaviors [3], and therefore interest in exploring their behaviors and particularly their resilience remains high. The National Academy of Sciences (NAS) defines resilience as “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" [4]. Generalizable and comprehensive approaches to understanding and quantifying SDN resilience, particularly under complex scenarios, remain lacking, and even alignment to definitions and terminology is inconsistent [5]. A strong suite of resilience analytics and stress testing tools are needed to better understand how we can build and support resilient SDNs [6].

Much prior work on global resilience focuses on macroeconomic data, such as GDP, global imports or country-to-country trade flows, and associated analyses such as graph statistics [7,8,9,10]. Starnini et al use a macroeconomic model to simulate network shocks [11]. Going to firm-level or multi-tier networks, Schweitzer et al build firm-level financial networks clearly indicating nodes with more central roles [12]. Gereffi et al analyze supply chains for medical supplies at multiple levels including country level relations and firm level [13]. Sigler et al use macrodata of sectors by country to identify clusters of sectors with implied connective networks [14].

Ji et al use big data from both supply and demand to synthesize aggregate SDNs [15]. Research by Simangunsong et al address supply chain risk, uncertainty and trust [16]. Capaldo & Giannoccaro identify local graph structures and impact on trust [17].

One major challenge is that few firm-to-firm relationships exist in the data, so we must infer them. A natural solution is to pose the problem as a Hitchcock distribution from combinatorics. This is a bipartite network flow problem in which nodes have either a supply or a demand and edges have a transportation cost and capacities. The goal is to allocate flow on edges such that total cost is minimized, capacities are respected, and nodes' supplies or demands are accounted for. This has been solved in many ways, but perhaps most notable is the algorithm by Ford and Fulkerson [18].

Financial networks maps have served as a proxy to effectively map and analyse the interdependencies of SDNs to uncover patterns, efficiencies, and vulnerabilities within industry sectors [19,20]. Supply chain resilience and robustness, as a fundamental feature for financially sustainable operations and demand-side markets, are dependent on network type and structure to maintain functionality during disruption, and to mitigate risk diffusion and propagation [21,22]. Using temporally-dynamic microeconomic metrics of companies indicative of liquidity, access to credit, and inventory turnover, among others, thus provide insight in in their financial capacity to recover after shock events.

3 Participant Tasks

A total of nine teams, including DARPA, are participating in this Resilient Supply Demand Networks program.

DARPA has framed and coordinated the research tasks as outlined in the introduction. DARPA has organized representative use cases including a) metals and critical minerals, e.g. copper, niobium, bauxite; b) food security, e.g. chicken, tomatoes; and c) pharmaceuticals e.g. heparin, atropine. These representative SDNs are all critical resources for industry, health, military operations, and international stability; and all could be impacted by shocks such as natural disasters, export controls and so on.

Accenture Federal Services (AFS) has provided a variety of supply chain data, (e.g. country-to-country copper trade flows, financial risk ratings for firms), as well as expert process diagrams. Additionally AFS has provided a cloud-based instance with graph-based data store, SDN ontology and sample computational notebooks (e.g. Jupyter) for supporting data-science workflows.

Two Six Technologies is focused on generating SDNs with generalized tooling: including collecting contractual data, extracting information via NLP logic and LLMs, connectors to open source data (e.g. EDGAR and USAspending.gov), and inferring SDN relationships. They introduce a new algorithm to solve the Hitchcock problem on non-bipartite graphs using an economic gravity model for edge costs. These capabilities are assembled into containerized services for on-demand SDN and insight generation. Leveraging DevSecOps, they offer a comprehensive integration platform for others to deliver their services.

Uncharted is assembling licensed data into a graph model, including granular bill-of-lading data from customs documents. Interactive visual analytics are be used to discover and assess relationships in large graphs by combining and extending hierarchical graph aggregation and edge bundling [23,24]. Uncharted is creating visual analytics to inspect neighbourhoods, highlight up- and down-stream relations, flag data gaps, provide selection for local subgraphs (Figure 2), compute simple scenarios (e.g. removal of Chilean sources) and corresponding resilience globally and locally to determine weak links.

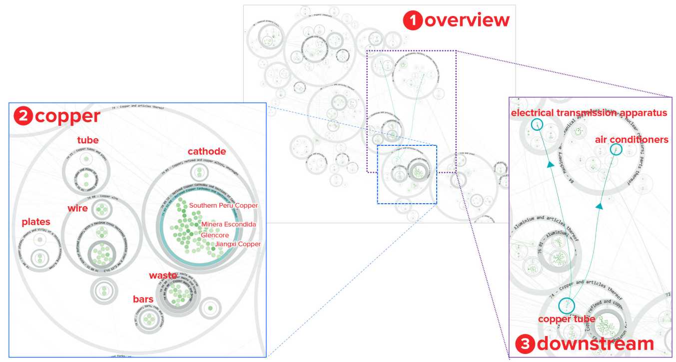

Fig. 2. Sample copper SDN (1) overview of hundreds of companies in network (2) zoom in to copper neighborhood including wire, tube, etc. with some individual companies labeled, (3) downstream connections from copper tube to air conditioner and electrical transmission manufacturers.

The University of Oklahoma (OU) is inferring network edges and nodes based on procurement relations and contract data with linear operators to forecast future nodes, links and associated values. OU is also modelling network risk and supplier survivability to understand network evolution and vulnerabilities in government procurement contracting using Bayesian Estimation. On top of these OU is creating visual analytic components to compare SDNs and enable what-if scenarios, disruptions, and exploration of cascading effects, together with Arizona State University (Figure 2).

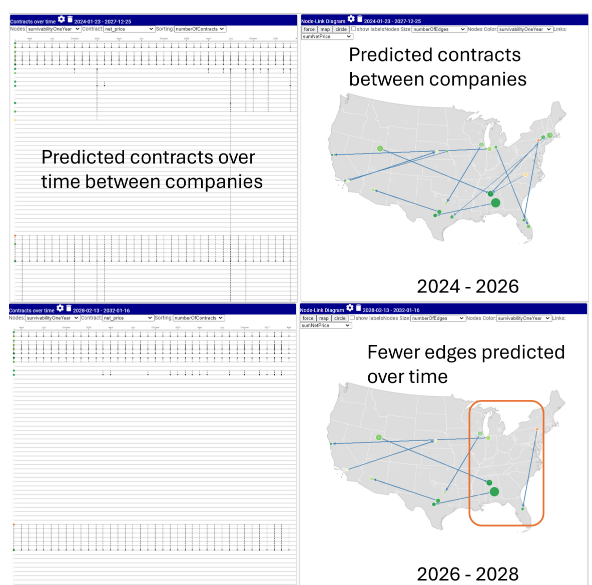

Fig. 2. Two connected components (left/right) are shown between two prediction target times (top/bottom). The left component shows predicted contracts between companies over time. The right component shows contracts in the time area between companies. Note that fewer edges are predicted from 2026 to 2028 (red box).

Stealth Software Technologies, together with Professors Peter Adriaens and Seth Guikema of University of Michigan, is creating graph-theoretic analytics for SDN fragility and recovery, as well as enriching SDNs via financial data and statistical modelling. This includes statistical analysis of SDN graph structure properties which will be used to train models to infer missing structure. Financial models enable testing of financial resilience to external shock events with impact on credit risk impacting event response.

RTX BBN is focused on SDN forward and reverse stress and mitigation testing based on the SDNs provided by other performers. Forward stress testing involves simulating counterfactual scenarios and observing the impact of those scenarios. Reverse stress testing is the identification of the set of stress events that could cause a given (unacceptable) SDN disruption. RTX BBN's micro-economic agent-based models [25,26] are informed by and themselves inform, computable general equilibrium modelling [27, 28] at USC. The simulations operate over SDNs that are supplemented with information from real-world current and historical data and shock/resilience surveys conducted by The OSU and NDSU. Clarkson University contributes a variety of graph analytics to augment shock, stress, and mitigation designs [29]. BBN's forward simulations model the response of a world state to the injection of some shock or stress as might result from such as disruptions to supply or finance. The reverse stress tests provide a probability distribution of the originating conditions and possible subsequent events that lead to some outcome or state of the SDN.

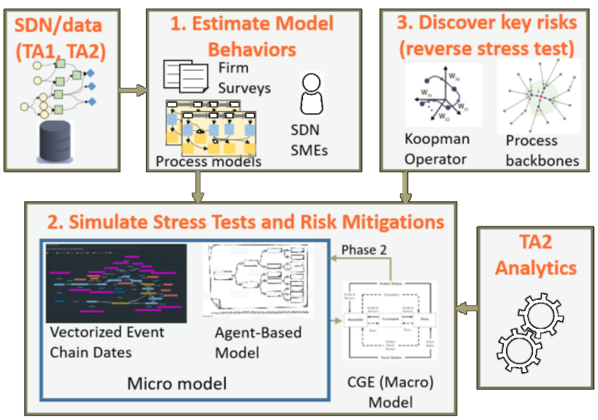

Fig. 3. RTX BBN SDN stress testing and mitigation simulation.

The RSDN Technical Area 3 team, RTX BBN, USC, OSU, NDSU, Clarkson, simulates the performance of supply and demand networks (SDNs). Behaviors of the networks and their component parts (e.g., financial institutions, commodity brokers, product consumers), are modeled by a hybrid micro- and macro-economic model based on agent-based models of entities in the network and computable general equilibrium (CGE)models of the economy as a whole, respectively. The simulations produce time-series state information for the network that may include the injection of counterfactual conditions such as shocks and stresses, as well as potential (pre-disruption) mitigation and (post-disruption) resilience/recovery responses. The shocks and stresses may be both predefined and derived automatically from analysis of the structure and dynamics of the graph. Microeconomic behaviors and the resilience strategies and outcomes are informed by international surveys of businesses conducted by the team. Where observations of portions of the network are unavailable, the graph is supplemented with synthetic data derived from machine learning models trained on representative data and qualified with their respective uncertainties. The simulations run in a flexible architecture that allows dynamic insertion of analytic and state-estimation capabilities. In future work that flexibility will be used to include reverse stress testing (i.e., estimating the probability distribution over potential causes of an observed or hypothesized disruption). As the performance of the SDN is characterized high-dimensional time-series, so too are joint behaviors among components of the network. The resulting modes of concomitant behaviors, or, patterns of life, among graph participants may be learned by available machine intelligence. That representation could identify risky or inefficient resilience actions or classify complex interactions suggestive of undesirable behavior such as money laundering, insider trading, unfair trade practices such as excessive government subsidies, and inefficient business responses to supply-chain disruptions.

West Point (United States Military Academy West Point), contributions focus on the connection between understanding real-world DoD SDN's and building immediately implementable risk assessments and mitigation policies. They are working on adapting and improving their financial risk model [30] and include risk assessment and methodology for decision-making [31] within the scope of the RSDN program. The risk assessment methodology which is founded in the DELPHI method [32] includes; a financial risk model; interviews with subject matter experts; collection and curation of multi-tier real-world DoD SDNs, e.g. for food security based on site visits including contract requirements such as surge production commitments; and calculations built on real-world data.

U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) is the government evaluator for the RSDN project. Its role is two-pronged: it supports the program with integrative technical work, and it also conducts evaluation of both the holistic program and individual performers. The technical integration works includes data set generation and synthesis, advisory support for technical integration, development of testing support tools, and cross-program coordination. Of particular note in this work is ERDC's prototype methodology for generating synthetic, plausible supply chains using a large language model, which could be used to create plausible supply chains or used to help fill in blind spots and gaps in datasets. ERDC's evaluation work includes coordination and assessment of evaluation events and associated metrics, as well as interim progress tracking. Of note in this work is the generation of a prototype comparison baseline solver, which can be used to simulate different shocks and a limited number of initial mitigation strategies. Additionally, ERDC has develop qualitative and quantitative performance key performance indicators (KPI) for program evaluation themes, including completeness and confidence (e.g. scope, fidelity, timeliness); quality of stress-testing (calibration, back-testing); a force multiplier assessment (e.g. pre-shock fragility and risk, mid-shock impact, post-shock mitigation). Other assessed topic areas include analytics coverage, tool usability, and quality of resilience assessment, uncertainty analysis, and imputation. Through our roles as both integrators and evaluators, ERDC is contributing its groundbreaking work in resilience, stress testing, network science, decision analytics fusion.

4 Virtual Panel and Schedule

Each panellist has extensive experience with network analysis from different perspectives. Some companies are academic research organizations exploring new computational models. Some are software research services and product companies, looking to innovate and translate research into future re-usable software. Some are government agencies, bringing the voice of the end-users and providing significant analytical approaches already in use in specialized applications.

The panel will be conducted virtually, e.g. via conference zoom, with one or two panellists attending in person as feasible. The virtual panel will offer sufficient time for interaction with the audience. The panel organizer will act as convener, manage the schedule, coordinate audience participation and moderate as needed. The 60 minute schedule is planned as follows:

0:00	DARPA introduction	5 min
0:05	Each team member present 5 mins each	40 min
0:45	Q&A with audience participation	15 min
1:00	Close	

5 Challenge questions

There are numerous challenges in attempting to construct global SDNs and assess resilience. The starting point of an SDN is significant challenge. What resolution is required to model an SDN: (a) flows between countries, companies, facilities, products, or down to lots? (b) the top 100 suppliers, the top 10,000 suppliers, 1 million suppliers? (c) how many tiers are required, and which branches are significant in a tier? (d) what data is available to model ground-truth: the data is so fragmented can any reasonable ground-truth be constructed and at what resolution?

Given a partial SDN, many models can be constructed to: (a) enrich the network with a wide variety of data (risk) attributes, such as financial, geographic, political, transport, quality, ownership, compliance and so on; (b) detect data gaps, (c) impute missing data, (d) compute network fragility. How is the imputed data to be assessed? Do users need to curate the results from multiple imputation models and how might that work? Fragility can be computed in many ways, and how is fragility to be assessed given potentially tens to hundreds of risk attributes? Can visual representations scale to the required resolution of the SDN? When these SDNs are used for training of ML and AI which are used to impute missing connections, what degree of error propagation is being magnified in the system?

Then, given an SDN and a scenario, there are many possible ways to forecast and simulate network responses, including forward and reverse stress tests, agent-based models, computable general equilibrium, process models, and so on. What is the confidence in the model given uncertainty in the SDN? Can the models capture real-world phenomena such as surge production to meet demand shock, or substitution effects? Models can be executed in response to given scenarios, but can they be used to identify latent risks not relevant in prior SDN disruptions? And so on.

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