AN OPEN-SOURCE TOOL FOR DIGITAL MAPPING OF MULTI-TIER SUPPLY CHAINS FOR VISIBILITY AND EMPOWERING RESILIENCE

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1 Introduction

Both upstream (aka demand side, bullwhip effect) and downstream disruptions (aka ripple effect) have crucial effect on not only operational efficiency of supply chains, also for surviving in catastrophic events. Despite the upstream disruptions, downstream disruptions tend to have deep uncertainty in which the timing and possible impacts are quite challenging to forecast. Only with end-to-end visibility of the supply chain it is possible to develop best mitigation plans for these unforeseen disruptions which require digital mapping the physical multi-tier supply chain.

Existing supply chain mapping tools capability are limited mostly with web scrapping for notification. Provided risk analytics tools are relying on qualitative surveys. Rather, there is a need for a digital supply chain mapping and visualization tool that enables defining and monitoring various risk related KPIs such as node and flow complexity, density, node criticality of the network as well as time to survive (TTS) and recover (TTR) analysis. Furthermore, that tool need to be accessible to all internal and external stakeholders of the supply chain with minimum software, hardware and skill requirement. Hence, in this paper, we present our online open-source digital tool for this need as a software as a service (SaaS) that runs on one of the largest on-demand cloud computing platforms as infrastructure as a service (IaaS). Our tool provides researchers an infrastructure to develop further analytic capabilities including a Bayesian analysis to anticipate the likelihood of the disruption scenarios along with their duration as well as combinatorial and simulation methods for developing the best mitigation plans during the disruption. Furthermore, primarily small and medium size enterprises benefits from our tool by removing the cost and skill barriers needed to deploy advanced analytics solutions. Furthermore, it has the potential to support public bodies for designing their service networks to individuals including humanitarian and pharmaceutical supply chains.

The rest of the paper is structured as in the following. A structural background of the problem, supported with relevant literature will be provided in Section 2. Insights gained from interviews with supply chain practitioners is discussed in Section 3. Section 4 gives an overview of the framework proposed. Software technologies used in developing the supply chain mapping and analysis tool is presented in Section 5. Social impacts of the tool are investigated in Section 6 and finally the paper concludes by discussing the future research directions in Section 7.

2 Background and motivation

Globalization comes with its price. Making supply chains leaner and more cost effective, namely just-in time, make them more vulnerable to various risks from many factors. While fluctuations in workforce like strikes, process shocks like breakdowns or cancellation of transportation routes causes disruptions from material flow, energy shortages, financial shocks like hyperinflation, geopolitical shocks as in Ukraine war or climate related shocks such as natural disasters as well as COVID-19, the greatest known in the modern supply chain history. The World Economic Forum also points the "collapse of a systematically important supply chain" as one of the most important risks in the global economy for the upcoming years (World Economic Forum, 2023).

Supply chain disruptions and their propagation have been the major risks in the continuity of business, health, education, and social services. From the economic point of view, particularly the pharmaceutical companies that make the most of the industrial production of Ireland (CSO, 2022) followed by food and chemicals. Complex structure of these vital industries makes them vulnerable to the mentioned disruptions according to Engineers Ireland (2022). In addition to the manufacturing industry, essential services like health, education, and humanitarian logistics are being affected by shortages of medicines, and material, unavailability of a critical skilled workforce, and delay in procurement/maintenance of equipment that are the result of not getting effectively prepared mitigation actions to above disruptions (CIOS, 2023). Ongoing pressure on supply chains due to Brexit, political instability, and increasing energy prices/availability keep supply chain disruptions still the priority in risk scale and will preserve its position in the foreseeable future. Therefore, it is the right time to develop an easily accessible digital tool to enhance the resilience of Irish supply chains on any scale.

3 Interviews with Industry Stakeholders and Insights

To understand industry stakeholders' perspective and elicitate their requirements, we have conducted a series of interviews across the geographies, industries and positions. The following Figure 1 and 2 provide the descriptive statistics about interviews.

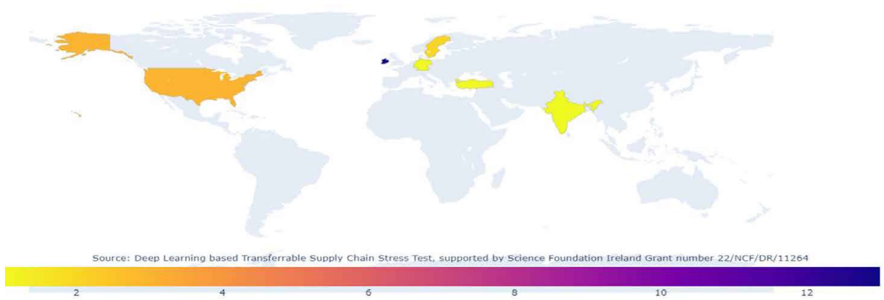

Figure 1: Geographical distribution of interviews

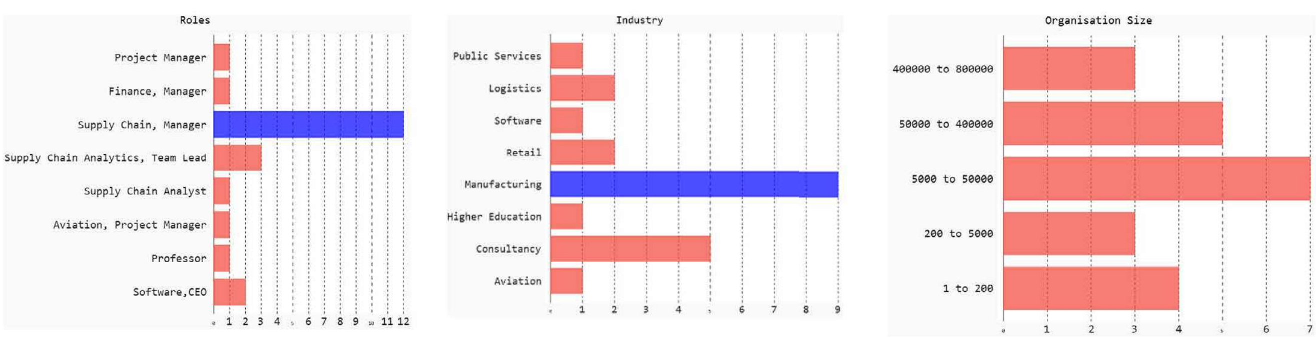

Figure 2: Roles, industries and organization sizes of stakeholders interviewed.

Stakeholder interviews are analyzed with Vos Viewer text analytics tool which grouped the feedback into three clusters as shown in Figure 3 below.

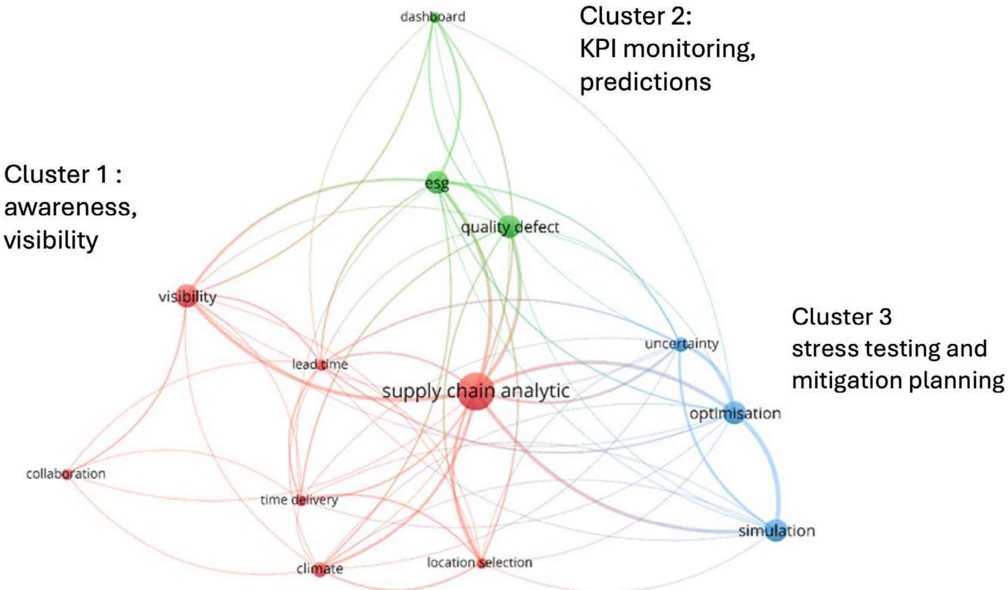

Figure 3: Stakeholder interview analysis.

Interviews with stakeholders and reviewing the relevant academic literature identified that for end-to-end supply chain resilience, there is a need for (1) a mechanism to anticipate the likelihood of disruption scenarios, (2) evaluating the impact of each scenario on the whole value chain, (3) ranking the severity of each scenario and node in the supply chain for all tiers (4) preparing and validating mitigation plans on dual sourcing, buffer allocation, re-allocating capacities and transportation of entities that robust enough for anticipated disruption scenarios while respecting economic, sustainability and societal concerns (5) develop the best course of action and test to react in case of a disruption occurrence in a computationally fast way to reduce response time. These requirements are grouped in three clusters as in Figure 3, Cluster 1: (1) and (2), Cluster 2: (3). Cluster 3: (4) and (5). Industry leader supply chain resilience solutions have lack of answering all those clusters together and focusing on only one of them.

4 Proposed Solution

To fulfill the industry requirement discussed in Section 3, we propose an analytical solution (see Figure 4) consists of several components. The first component is providing a mechanism to transform supply chain geospatial data and bill of material (BOM) into a graph model. While each node represents a component/subassembly/product/service in BOM and its relevant facility, edges represent the eligible material flow between facilities and between nodes in BOM. Next, for each facility node, the most likely disruption duration and probability of occurrence is computed through stakeholder historical records and publicly available data via web scraping. Disruption scenarios are fed into a stress testing decision model, to understand how long the supply chain can continue to operate in case of the failure of that node (time to survive, TTS, Simchi-Levi et al., (2015)). Then, a high-fidelity discrete event simulation model is used to validate the TTS values. Next, to overcome the difficulty of having analytic solvers and discrete event simulation tools, a metamodel (artificial neural network, ANN) is developed for TTS analysis. The result of TTS analytics is shared with supply chain planners to inform them that if corresponding suppliers' time to recover from a disruption (TTR) is longer than TTS so that they need to develop actions to improve (shorten) their TTR. After that, another analytical model is being used for generating mitigation plans with given TTR values, TTR analytics (or mitigation planning) by taking into account the sustainability and social impact of the plans. Another discrete event simulation model to consider compound disruption scenarios, complex interactions between nodes, and the behavior of the supply chain under uncertainty over time is being used for validation. Finally, another ANN is developed to make mitigation planning and simulator agnostic to technologies. In the last stage, deep transfer learning methods is employed for adapting trained ANN to individual stakeholders' supply chain. The overall framework is called as Supply Chain Mapping and Analysis Tool (SCMA).

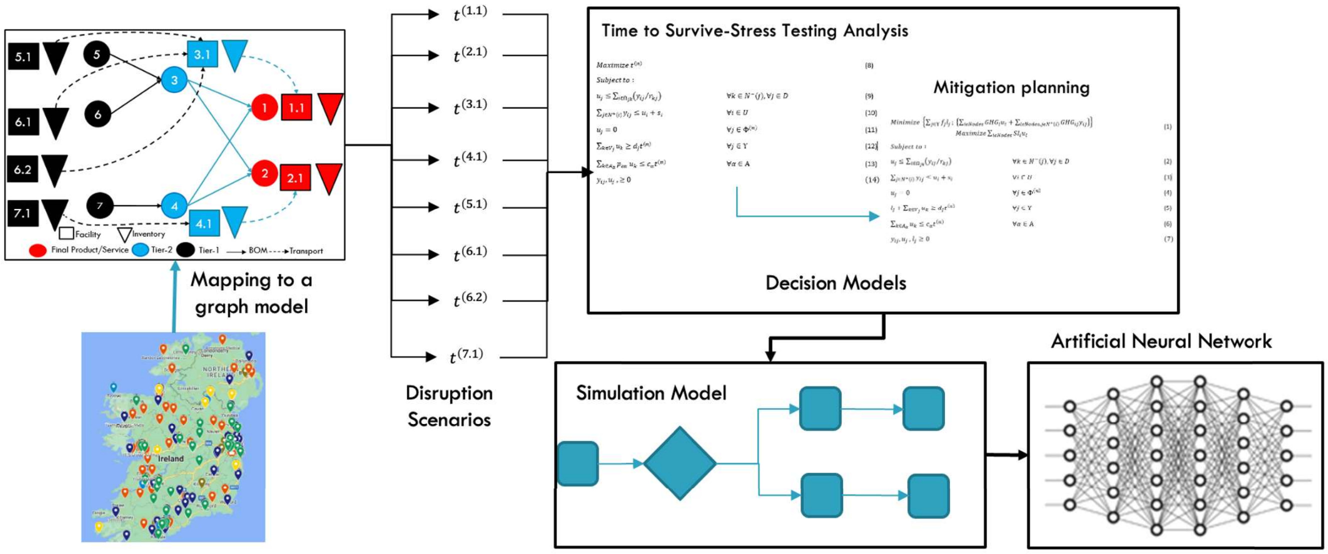

Figure 4: Supply Chain Mapping and Analysis Tool Workflow

5 Supply Chain Mapping and Analysis Tool (SCMA)

5. Overview of SCMA

Stress testing framework is developed on cloud services to facilitate any stakeholder in the supply chain can access anytime and anywhere without needing special/advanced software and hardware infrastructure. A screenshot for demonstrated BOM and mapping on geospatial data through SCMA is shown in the following figure.

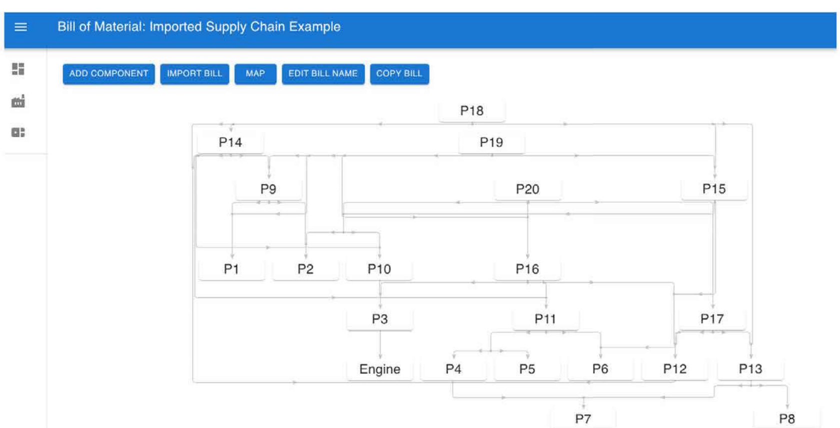

Figure 5: A demonstrated bill of material

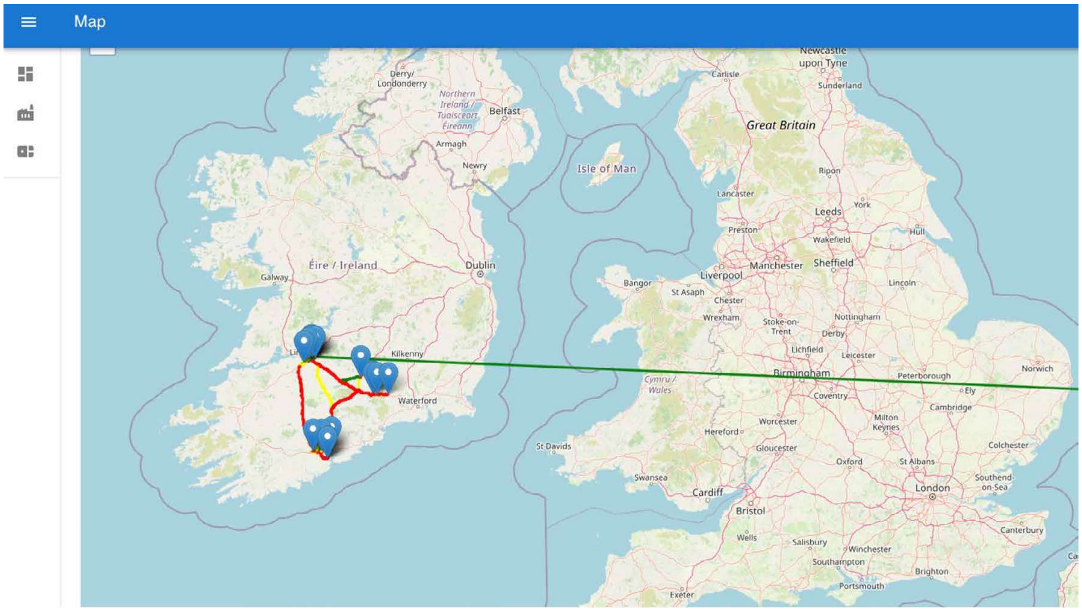

Figure 6: Geospatial mapping of supply chain network

In the following subsections, details of supply chain mapping components are explained.

5.2 Infrastructure and software technology

Below is a diagram of our application infrastructure. It shows the cloud services and libraries we make use of in our application, separated into the Front-end and AWS Cloud.

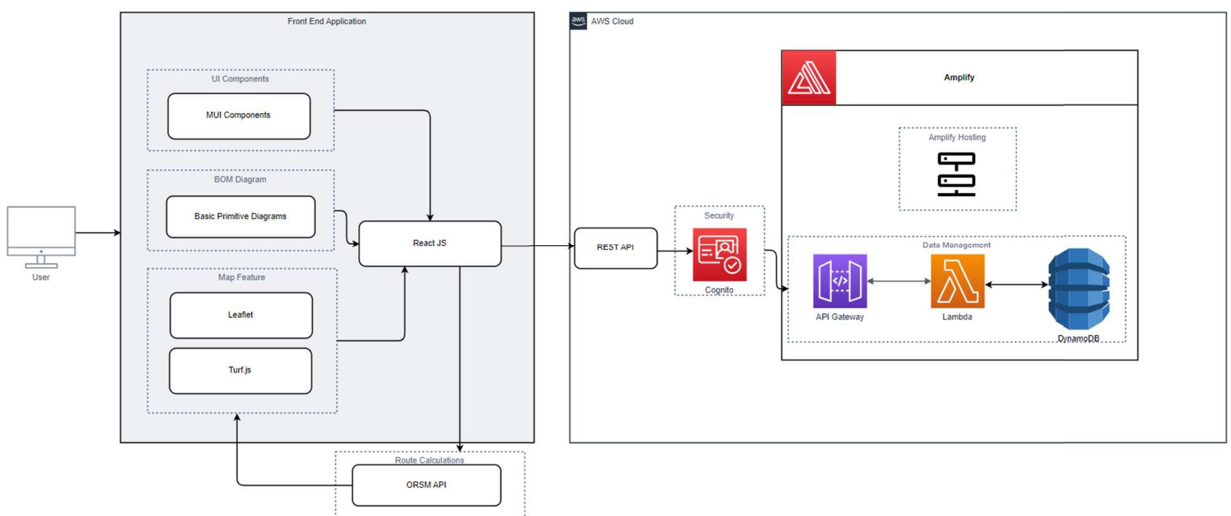

Figure 7: SCMA Infrastructure

5.2.1 Amazon Web Services (AWS)

AWS (AWS, 2024) is one of the most popular and robust cloud service providers on the market, with over 200 services. We have made extensive use of AWS to handle essential but time-consuming development tasks and to host the web application.

5.2.1.1 AWS Amplify

AWS Amplify is a service for full stack web development offering features for hosting and building back-end infrastructure. In our implementation, we used Amplify to quickly build the data management section consisting of API Gateway, Lambda functions to pass requests to the database and the actual DynamoDB database. We also use Amplify hosting to host the web application. When a change is pushed to the master branch of our code repo, stored in AWS CodeCommit, Amplify Hosting automatically takes the changes, builds and deploys the application. Making use of Amplify allows us testing our application in a live environment much quicker than if implementing each of these services on their own.

5.2.1.2 AWS API Gateway

The Application Programming Interfaces (APIs) Amplify created are made using AWS API Gateway, a solution for API creation, publish and management of APIs. Creating these with Amplify has traded some robustness for more streamlined implementation, but for our needs this implementation has proven very effective.

5.2.1.3 AWS Lambda

AWS Lambda is a serverless compute service for running specified functions without the need of having these functions on a dedicated server. Amplify created a lambda function for handling the data received by any API requests to the database, validating any data sent as part of the request and running the DynamoDB commands.

5.2.1.4 AWS DynamoDB

AWS DynamoDB, a fully managed NoSQL database service, meets our application's database requirements with fast, predictable performance and seamless scalability.

5.2.1.5 Amazon Cognito

Amazon Cognito is an Identity and Access management service we have made use of to handle the sign in, sign up and user authentication in our application. Cognito securely stores the user data inside AWS and provides authenticated users with the token required to access the APIs.

5.2.1.6 React JS

React JS is a front-end Javascript library used mainly for building user interfaces. It was chosen for emphasis on reusable components, the availability of additional tools and libraries it supports and how its unidirectional data flow make debugging easier.

5.2.1.7 MUI Component Library for User Interface (UI)

MUI, formerly Material UI, is a React component library that offers professional looking and robust UI elements. These elements are easily customizable and come with extension documentation.

5.2.1.8 Basic Primitive Diagrams for React

Basic Primitive Diagrams is a diagram library for visualization and analysis of node-based bill of material (BOM) diagrams such as organizational charts, family charts and business ownership diagrams. The version of Basic Primative we are using is made specifically for React applications. The diagram we are using is the Family diagram as this allows the nodes in our BOM diagrams to have multiple parents. The library comes with extensive features for diagram layout customization and interaction.

5.2.1.9 Leaflet

Leaftet is the library we are using for the Map display in our application. It is a lightweight and easy to use library.

5.2.2 OSRM (Open Source Routing Machine)

OSRM is a high-performance routing engine designed for calculating routes. It contains real-world map data from OpenStreetMap, allowing it to compute optimal routes efficiently. We use OSRM to determine the driving routes between different locations in our application. By querying the OSRM API, we obtain detailed route geometries that we can display on our map.

5.2.2.1 Turf.js

While Leaflet can display the map and coordinate data effectively, we made use of Turf.js for advanced geospatial analysis and calculations. Turf.js helps us measure distances, calculate areas, and perform various spatial operations on the geographic data in our application.

6 Impact

The proposed solution essentially will provide a tool to decision-makers in industrial and public organizations to strengthen their supply chain against external shocks. In addition to its benefit for organizations to improve their business-related performance indicators, having such a tool and strengthening supply chains will have a direct impact on society in several ways as supply chains are the veins of global and national ecosystems. The developed tool will enable the delivery of essential goods and services in an uninterrupted way. This will help society to face product and service shortages and result in reduced price inflation. Furthermore, the developed tool will support public decision-makers to robustly plan humanitarian logistics activities in case of catastrophic natural disasters. The COVID-19 pandemic also showed the need for fast reconfiguration of existing manufacturing facilities for producing urgent health products like ventilators. This unexpected global disruption requires reconfiguring the whole supply chain in a short time period as well. The proposed tool has the potential to support governmental agencies, healthcare, and industry in their manufacturing repurposing efforts during crises.

7 Conclusion and Future Research

In this paper, we presented a cloud based digital tool, supply chain mapping and analysis, to evaluate vulnerability of a given supply chain and mitigation planning by considering economic and societal impacts of disruptions. Details of the software infrastructure are presented. Recent global disruptions brought significant insights and baselines for both business and public organizations in terms of evaluating the impact of them on their supply chain. Hence, the proposed solution in this paper will be extended to include various other impacts such as : (1) complaints received from clients who are commercial customers for business organizations or clients for public organizations regarding access to or delays in products or services provided (2) market share and lost sales for business organizations, (3) productive capacity lost in manufacturing/service facilities (4) response time/waiting time for clients (5) stability in workforce numbers (6) number of times production/service interrupted due to supplier problems. Further graph based analytical methods to evaluate complexity of given supply chain networks as well as efficient multi-objective solution methods for TTS and green TTR models will be investigated.

Acknowledgements

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