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SIMULATING COUNTERFEIT PERSONAL PROTECTIVE EQUIPMENT (PPE) SUPPLY CHAINS DURING COVID-19

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ABSTRACT

Increased demand for medical supplies, and specifically respirators and face masks, during the Covid-19 pandemic along with the inability of legitimate suppliers to meet these needs created a window of opportunity for counterfeiters to capitalize on the supply chain disruptions caused by a global health crisis. Both legitimate and illicit businesses began shifting their scope from sectors such as textiles to producing and distributing personal protective equipment (PPE), many of which were counterfeit or unauthentic products and thus unable to properly protect users. To study cost-effective disruption strategies, this study proposes a simulation-optimization framework. The framework is used to model counterfeiters' behavior and analyze the effectiveness of different disruption strategies for counterfeit PPE supply chains during the Covid-19 pandemic.

1 INTRODUCTION

The Covid-19 pandemic increased awareness about the importance of increased counterfeit goods, revealing the negative impact of these harmful products. While counterfeit supply chains have historically been a problem, the global health crisis demonstrated that counterfeiting is not only an Intellectual Property Rights (IPR) or brand protection issue, but that the trade in counterfeits also has negative consequences for the economy, public health, and security.

The emergency situation of the Covid-19 pandemic resulted in a shortage of personal protective equipment (PPE) for workers in the healthcare industry as factories manufacturing and distributing PPE were unable to satisfy increasing demand. This triggered unscrupulous suppliers and distributors to mass-produce substandard PPE at cheaper prices without following proper quality standards resulting in counterfeit PPE of lower quality. Without the protective power of genuine products, these harmful respirators negatively affect patients and healthcare workers, leading to an unsafe environment and resulting in continued pathogenic transmission.

Infections and deaths caused by Covid-19 might have been reduced if counterfeit PPE had not entered legitimate supply chains. This demonstrates the value of using simulation and other

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analytics techniques to predict counterfeiters' behaviors within illicit supply chains, not only during the periods of the Covid-19 pandemic but also in the case of possible future health crises.

To protect health frontline workers as well as the general population from counterfeit PPE, law enforcement and other regulatory bodies must identify the most effective disruption strategies. However, evaluation of potential disruption strategies is time consuming and entails many uncertainties due to potentially missing or incomplete data, rapid situational changes, and a general inability to forecast future events.

The volatile pandemic environment resulted in various unforeseen uncertainties including fluctuating demand and prices for products. For example, throughout the first two years of the pandemic, it was difficult to predict the spread of new variants, changes in national and international level regulations and policies, or the future trajectory of the virus. The inability to predict or predetermine scenarios lead to uncertainty in both legitimate and illicit supply chain operations. The first wave of active Covid-19 cases increased N95 demand by up to 17X (Premier 2021). While nearly all PPE products increased in price after the start of the pandemic, the largest price increase was for 3M N95 masks, which rose from $0.11 to $6.75 each (6,136% increase) (Berklan 2020). The demand for medical products such as N95 respirators also drastically rose and fell throughout the pandemic, often responding to changing regulations regarding mask mandates across various jurisdictions.

In this study, a simulation optimization framework is proposed to study the effectiveness of different disruption strategies for counterfeit PPE supply chains considering the uncertainty. This article proceeds as follows. In Section 2, we present a literature review that outlines existing research on counterfeit supply chains using simulation and explains the contribution of the proposed framework that specifically addresses counterfeit PPE (rather than more general counterfeit) supply chains. Sections 3 and 4 outline the problem statement and introduce the proposed simulation-optimization framework. In Section 5 we show the numerical experiment. Finally, the Conclusion (Section 6) emphasizes the importance of a simulation-optimization framework for evaluating potential disruption strategies and informing what enforcement actions should be taken to combat counterfeit PPE supply chains.

2 LITERATURE REVIEW

A related research area of the counterfeit PPE is the simulation optimization framework that incorporates counterfeiters' and disruptors' behaviors. In this section, the literature on counterfeit PPE and the related simulation optimization framework are reviewed.

2.1 Counterfeit PPE Research

The demand for PPE has risen sharply since the outbreak of the Covid-19 pandemic (OECD 2021). However, border closures, disruptions in supply chains, and production in insufficient quantities meant that this increasing demand for PPE was not met. Hence, counterfeiters saw this as an opportunity to take advantage of growing demand by increasing the manufacturing of counterfeit PPE and finding successful ways to market it (OECD/European Union Intellectual Property Office 2021). This was done through social media, ecommerce platforms, and online marketplaces (OECD 2020). The rise in ecommerce and counterfeits during Covid-19 raises the issue of trademark liability for the sale of counterfeit goods by third parties and platforms as current legal frameworks were created for brick and mortar settings (Kammel et al. 2021). Not only do these counterfeiters infringe on other legitimate brands and capitalize on the crisis by price gouging, but the counterfeit PPE they offer also poses significant health and safety risks as it does not adequately protect individuals as legitimate PPE would. To combat the dangers of counterfeit PPE, there have been changes in customs control policies. Despite the efforts of customs and other enforcement agencies, counterfeiters continue to devise new ways to counter such efforts, which is why it is crucial to study counterfeiter behavior and analyze disruption strategies for counterfeit PPE supply chains.

To avoid counterfeit PPE being distributed to healthcare workers or patients, all stages of the PPE supply chain, from production to delivery, must be strictly managed and controlled. Previous research has studied disrupting counterfeit PPE by managing risks on each stage of the supply chain (Clauson et al. 2018; Shen et al. 2021; Schumacher et al. 2021). Clauson et al. (2018) propose that blockchain technology can be effectively applied to supply chain management in the healthcare and medical industry, an approach that decentralized managing medical products received from each supplier, distributor, and retailer to the final users. Quality inspection could be applied in each of the working stages of PPE supply chain and managed by the blockchain adoption approach. Further, Shen et al. (2021) examine the blockchain adoption with quality inspection could help effectively combat counterfeit PPE sellers/distributors deployed at the supplier stage. However, Schumacher et al. (2021) mention that the complexity of PPE supply chains may increase the probability of counterfeit products as buyers often do not know their suppliers and their ability to monitor products of inferior quality.

In addition, PPE supply chains continuously change over time. Due to the high demand for PPE during the Covid-19 pandemic, many companies that were never previous producers of PPE started production (Schumacher et al 2021). Given the constant evolution of counterfeit PPE supply chains must be considered when developing appropriate disruption strategies.

2.2 Counterfeit Supply Chains Using Simulation

Simulation is a powerful and widely used management science technique for imitating the complex operation of uncertain real-world scenarios as it evolves over a period of time (Anzoom et al. 2022). Scholars have evaluated the effectiveness of existing policies or interdiction measures to combat illicit supply chains through simulated illicit trading environments. According to the latest illicit trading framework (Anzoom et al., 2022), drugs are classified as physical products in the same category as counterfeits. In the application of illicit drug supply chains, Caulkins (1993) simulated the demand of a local drug market and studied possible disruption operations considering the response a street market might have to a crackdown. Dray et al. (2008) designed an agent-based simulation model to study the interaction between individuals and the supply of heroin in a drug market. In contrast with interdictions by local police, they simulated three experimental conditions of drug law enforcement operations including random patrol, hot-spot policing, and problem-oriented policing. Rydell et al. (1996) examined the different existing intervention policies by constructing a corresponding simulation model on the effect of government interventions over time depending on simulating the market size and the curves of demand and supply for certain consumer illicit goods. In addition, Magliocca et al. (2019) used simulation to predict trafficking routes for the certain drugs by simulating traffickers' path selection over the times period after interdiction. Under the limited range of specific areas for departure and destination, the simulating trafficking routes are generated based on organized groups' and individuals' decisions and controlled by the shortest route, lowest cost, lowest risk, and the relevant policies or conditions of the transit countries. In general, current scholars of illicit drug trafficking researchers apply simulation on spatial, temporal, risks of arrest, and scale of the demand and supply of the illicit product supply chains. Simulation can be applied not only to counterfeit trades and policy evaluations. Kovari and Prupt (2012) simulated the supply, demand, and different policy interventions based on population structure, criminal indicators, and economic behavior to assess the impact of policy intervention on human trafficking in the Netherlands. Therefore, simulations can support law enforcement in evaluating operations' effectiveness and costs.

Some scholars focus on analyzing licit or illicit products and their transport and trafficking routes. In general, counterfeit trade is further classified as deceptive and non-deceptive (Anzoom et al. 2022); the main difference is the knowledge of the customers. Unlike luxury goods, consumers do not seek out counterfeit PPE. Counterfeit products may produce low-quality or fake print trademarks to be cheaper to sell. Therefore, some scholars focus on identifying counterfeit products in large-scale shipments through the trading documents or patterns of the product supply chain. Kretschmann and Munsterberg (2017) designed the simulation model based on the existing licit or illicit products for detecting illicit products in large volumes of shipments at borders. In addition, Ordiano et al. (2020) constructed the simulated route models for classifying the licit or illicit supply chain network based on the designated serial transit sites in regional- and continents-level (i.e., North America, Europe, or Mongolia) and selected the optimal connection scale from the links of these sites. Hence, due to lack of data acquisition and concealment of illicit business, simulation is the optimal method to help describe the changing environment of illicit supply chains.

This paper addresses a key research gap in the existing literature - the lack of a simulation-optimization framework to address the trade in counterfeit PPE. While previous studies have examined the use of simulation to analyze the uncertainty and unpredictability of PPE supply chains, these approaches are unable to consider counterfeiters' behavior including anomalies in supply chain patterns that occurred during the Covid-19 pandemic and evaluate the effectiveness of different disruption strategies. Other studies have also examined counterfeit supply chains products but have not specifically focused on the trade in PPE. The use of a simulation-optimization framework presented in this paper allows for the identification and evaluation of fluctuations in demand and price over time corresponding to key moments during the pandemic, thus providing a more holistic and accurate depiction of counterfeit PPE supply chains and allowing for identification of the best disruption strategies.

3 PROBLEM STATEMENT

Counterfeit PPE supply chains involve multiple participants all of whom must be taken into consideration when developing and implementing effective enforcement actions. The facilitators of illicit PPE supply chains include producers, wholesalers, distributors, and other counterfeit actors. The disruptors of illicit PPE supply chains include law enforcement, customs officials, and other individuals and agencies tasked with detecting and intercepting counterfeit products and related networks.

3.1 Counterfeit PPE Models

For this paper, we construct several types of counterfeit models based on real world investigations of counterfeit PPE supply chains. The ultimate objective of counterfeit producers is to maximize profits while minimizing the risk of detection.

Companies can sell products more directly from their business to end users through online ads (B2C) or they can sell (often larger quantities of) goods to other businesses or wholesalers who then distribute respirators to the end user (B2B). Additionally, producers of counterfeits often rely on shell companies or wholesalers to facilitate supply chain operations. In order to avoid detection and disruption, counterfeiters will use shell companies to transfer funds or assets. Shell companies are often used for tax evasion, money laundering, and to hide the identities of the company's real owner(s). Producers may also engage with wholesalers to sell larger quantities in order to increase profits and minimize risk. Because wholesalers are sharing the risk of the producer, counterfeiters must incentivize their respective wholesalers by sharing a percentage of their profits. Identifying shell companies and wholesalers and their relationship to the producer can be difficult and resource intensive. Therefore, this paper focuses on disruption strategies that take place further downstream in the supply chain. The use of a shell company increases risk of detection while the use of a wholesaler decreases risk of detection.

A general framework of counterfeit PPE supply chains is provided in Figure 1. All PPE supply chains begin with a counterfeit producer or factory that manufactures PPE. From this first node, producers either directly sell to the market or use an intermediary such as a wholesaler or shell company to advertise their products on B2C and B2B markets. Once an order is placed through online markets, the shipment of goods is fulfilled through the physical product flow which typically involves transport of goods through a port and a warehouse before ultimately being delivered to the end user or distributor. Producers may choose to rent a warehouse to store product at various locations for quick and efficient delivery to the end user or distributor. Products are moved through transit locations such as ports and free trade zones which can consist of air sea ports before storage at various warehouses located in closer proximity to the end user or distributor. While demand and sales price can fluctuate drastically at different times during the pandemic, the general structure of physical and information flows outlined in Figure 1 remains the same.

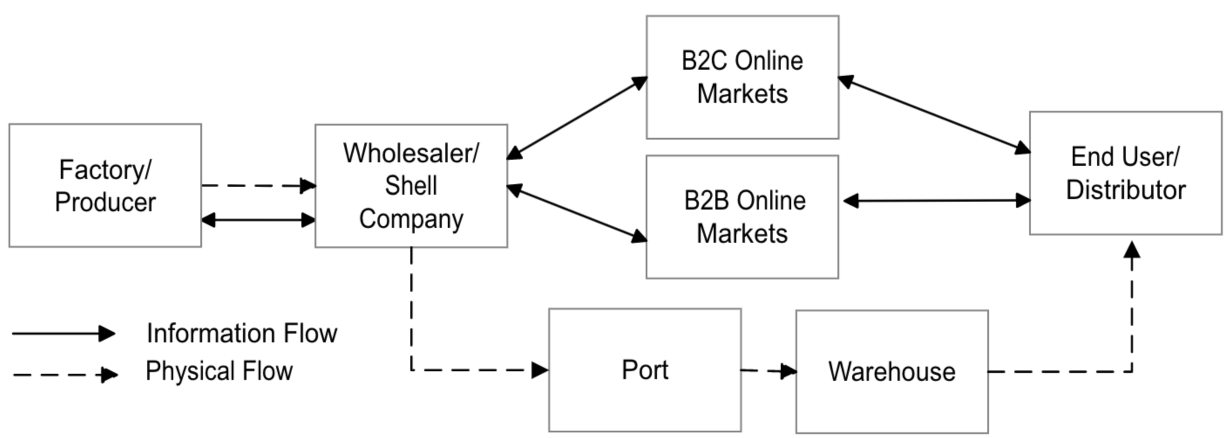


Figure 1. Supply chain network graph.

As previously mentioned, producers can engage in business to customer (B2C) or business to business (B2B) sales models. Counterfeiters determine if they will sell to end users (B2C) or distributors (B2B) based on demand and production capacity. Counterfeit producers may change their business models to increase profits and minimize risk. Counterfeiters constantly adapt and adjust their operations to consider the trade-off between maximizing profits and minimizing risk. Because counterfeit producers modify their strategy over time, disruption becomes less effective as investigation lead time increases. Therefore, the earlier in the supply chain counterfeits can be intercepted, the more effective the disruption strategy. They are often disrupted through the identification of anomalies in their business practices.

4 PROPOSED APPROACH

4.1 Proposed Framework

This paper proposes a simulation-optimization framework to evaluate the effectiveness of different disruption strategies. The proposed framework (Figure 2) uses simulation to generate all possible scenarios in the counterfeit PPE supply chain. To incorporate the uncertainty factors including fluctuations in demand and price over time during the COVID-19 pandemic, the simulation technique is used to generate different scenarios. The counterfeiters' behaviors, modeled as an optimization module, are used to understand as an optimization module to study their behavior on the operations of illicit supply chains under uncertainty. Finally, the statistical inference module decides the simulation replication to accurately represent the whole supply chain and related anomalies to develop appropriate and cost-effective disruption strategies.

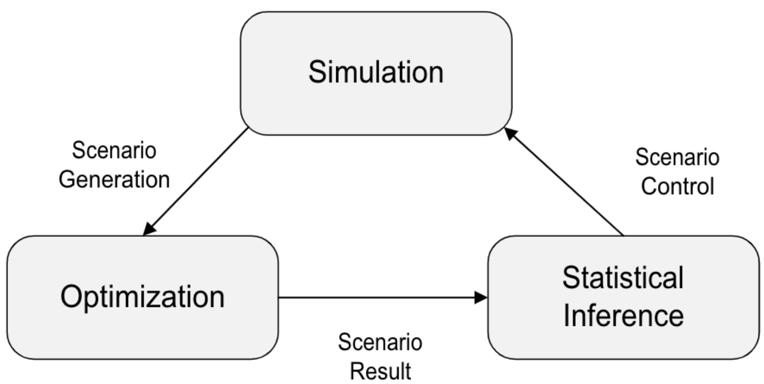


Figure 2. Proposed framework.

4.2 Simulation for Scenario Generation

In the simulation module, key Covid-19 events during the pandemic are collected as shown in Figure 3. These events are then used to create branches in a scenario tree shown in Figure 4. Each node in the scenario tree can have multiple children nodes accounting for possible cases of the corresponding event. These cases can be, for example, the worst case, average case, or the best case. As seen in Figure 4, we start from the root node which represents the probability of the case and the unchanged base values we have for the B2B and B2C demand quantities of each city and the corresponding sell price.

The whole timeline spans over 36 months, from January 2020 to December 2022. Each level in the tree accounts for one month. The root node is set as month 0. Hence, all nodes numbered 1 are for month 1, nodes numbered 2 for month 2, until the end of the whole timeline. This allows us to have several different combinations for the scenarios that the simulation module can generate.

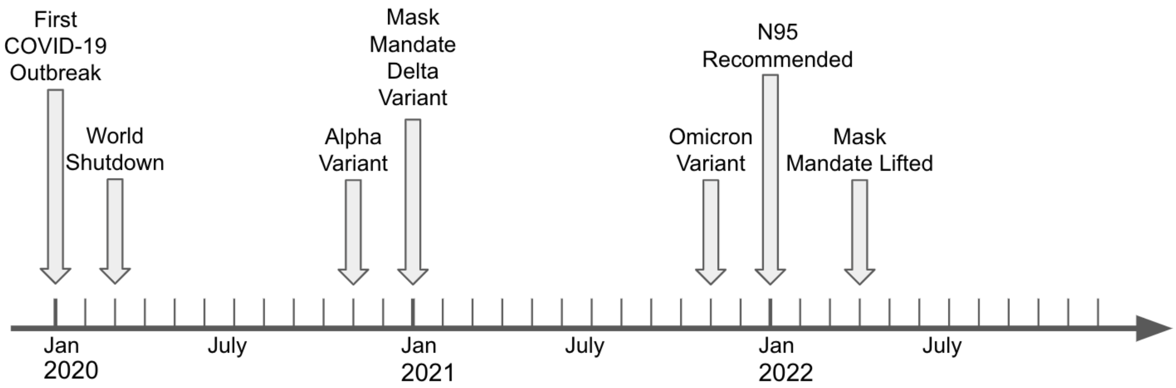


Figure 3. Scenario timeline.

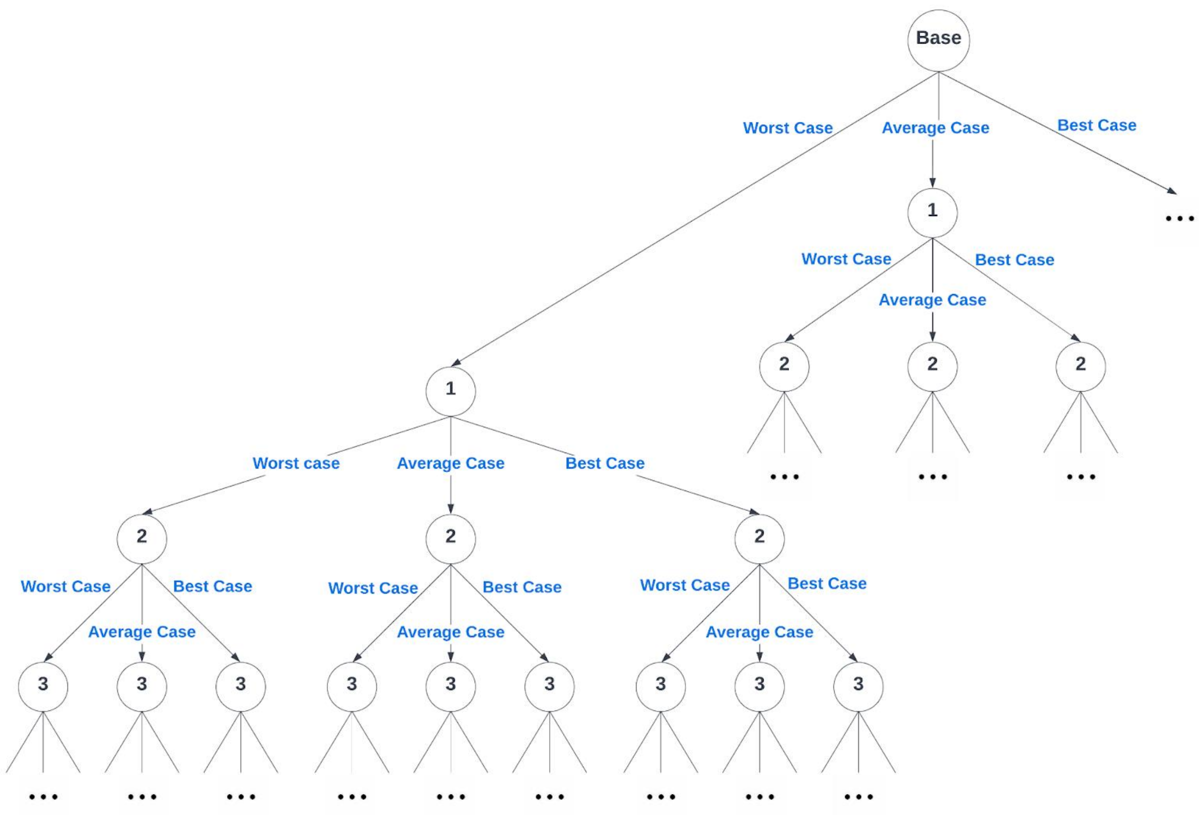


Figure 4. An example of scenario tree structure.

The scenario tree structure is used to model the uncertainty during the Covid-19 pandemic. In this case, each simulation run by visiting the scenario tree is a generated individual scenario. Each node in the scenario tree could store information regarding the month, standard deviation, and probability to later be used for generating the corresponding demand and price for the scenarios. Hence, running through the scenario tree multiple times would result in the generation of multiple distinct scenarios. As seen in Figure 3, the key Covid-19 events occur at months 1, 3, 11, 13, 23, 25, and 28. Hence, for these particular months when the key Covid-19 events occur, the standard deviation for that scenario tree node may be adjusted accordingly to ensure that the resulting scenario reflects these key events. Furthermore, the cases at each level in the tree may have varying probabilities of occurrence, depending on which each run through the scenario tree would take a different path resulting in a distinct scenario.

The simulation was implemented using the pandas (McKinney et al. 2022), NumPy (Harris et al. 2020), random (Van Rossum 2020), and xlsxwriter (McNamara 2022) Python libraries.

4.3 Optimization and Statistical Inference

Although counterfeiters change their operations of the illicit supply chains over time, they always follow certain objectives. Two major objectives are to maximize their profit and minimize the risk of exposing their identity. Despite the ability to gain significant profits, they also need to consider costs related to constructing illicit supply chains and maintaining network relationships with other partners. For the risk, they also need to consider the detection of operations, seizure of products, and being exposed to law enforcement or other entities. To mitigate risks of exposure and seizure, counterfeiters invest in concealment, corruption, and also evasion. These efforts to avoid detection must be considered when evaluating different disruptions strategies.

To model both counterfeiters' behavior and law enforcement's possible disruption strategies, we develop a bilevel optimization model to represent this adversarial relationship. Bilevel optimization was developed by Heinrich von Stackelberg (Stackelberg et al., 2011) to describe a leader-follower relationship. Each level depends on each other. In addition, the leader takes the follower's reaction into account. In the bi-level optimization model, the disruption decisions are modeled as the leader's decision while the counterfeiters' decisions on operating illicit supply chains are modeled as the follower's reaction. Counterfeiters also use several techniques to successfully avoid AI detection such as use of special characters to avoid key term detection.

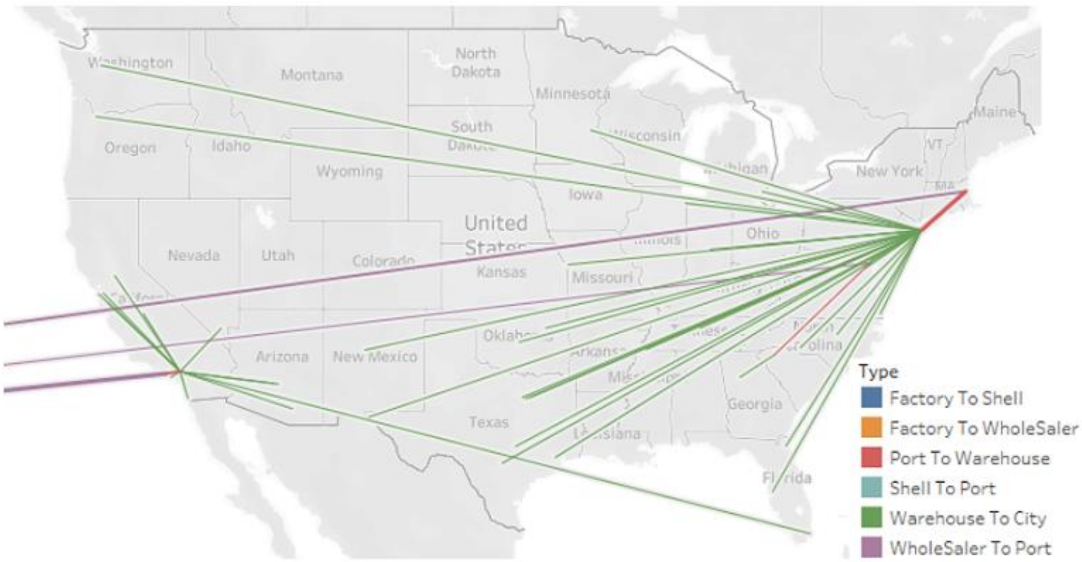
For the statistical inference, we applied the sample average approximation (SAA) method (Verweij et al. 2003). As the demand and price uncertainties in each city are modeled as a number of scenarios in the simulation module, the accurate estimate of the true problem needs to be derived. The SAA algorithm estimates the optimality gap and its variance of a feasible solution of the true problem. The optimal objective value of the true problem is estimated by the expected objective value of a number of scenarios.

5 NUMERICAL EXPERIMENT

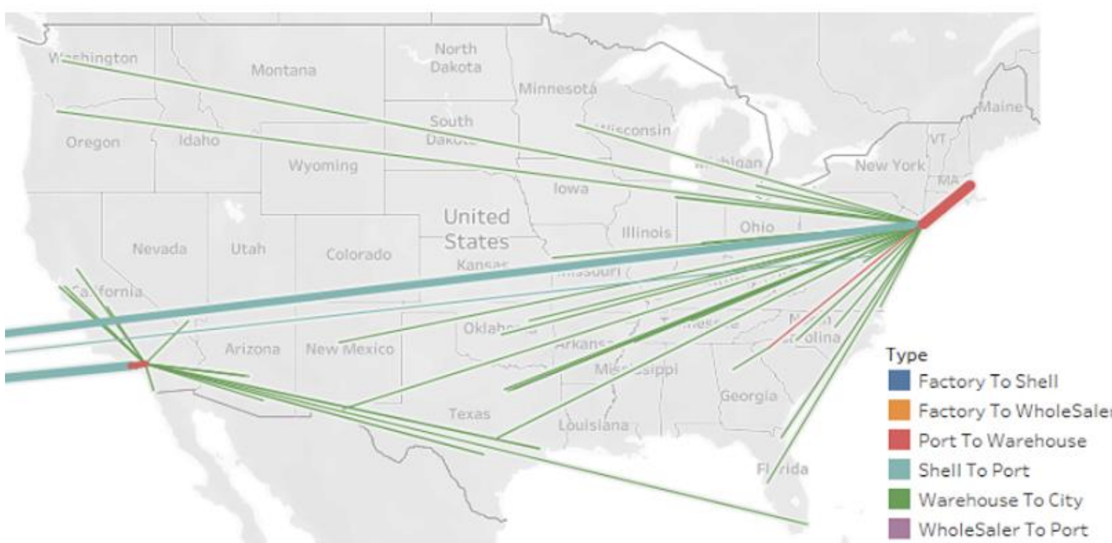
5.1 Optimization – Criminal and Disruption Models

The base model in this paper is the counterfeit model without disruption. Next, counterfeiter behavior is analyzed for each time period to better understand how they shift their supply chain operations to avoid disruption. The results are shown in Figure 5. First, the counterfeit producer will expand their facilities and production capability when they have sufficient money and resources to do so. Generally, expansion of production capabilities only happens in the first five months, which is similar to the cases observed in practice during the Covid-19 pandemic. From the base model, we observe that companies will focus on B2C sales in the earlier periods of the supply chain and later switch to B2B trade as shown in Figure 5(i) and 5(ii) below. In Figure 5(i), with the base model at T=1, a wholesaler is used. While in Figure 5(ii) with the base model at

T=19, there is increased use of a shell company by the counterfeit producer. This is largely in an effort to increase the scale of sales and subsequently, to maximize profit.



(i)



(ii)

Figure 5. (i) Supply chain base model at T=1. (ii) Supply chain base model at T=19.

6 CONCLUSION

This paper provided a simulation-optimization framework to examine an unaddressed problem - how to best disrupt counterfeit PPE supply chains during the Covid-19 pandemic. The evaluation of different disruption strategies is critically important as it identifies the most effective enforcement actions and informs what further steps should be taken. This framework is based on the available resources while also considering the current state of the supply chain.

There are several benefits to this proposed framework. First, the proposed framework examines supply chains over time, addressing the fluctuation of demand and sales price during each time period. Second, this framework allows for effective enforcement action. Due to the high level of uncertainty, there are several potential disruption strategies that need to be evaluated for effectiveness. Providing a prioritized list of potential actions allows for effective and informed enforcement that results in substantial and sustaining disruption of counterfeit supply chains. Finally, using a simulation approach to address uncertainties and generate possible scenarios provides solutions that can inform enforcement decision-making. The proposed framework provides key benefits by accounting for supply chain uncertainties and makes effective use of resources needed to implement enforcement actions in practice.

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