Advanced Engineering Informatics 64 (2025) 103084

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

Modelling and disrupting counterfeit N95 respirator supply chains☆

Edward Huang [a,*], Louise Shelley [b], Layla Hashemi [c]

[a] Department of Industrial and Systems Engineering, Auburn University, Auburn AL 36849, USA
[b] Schar School of Policy and Government, George Mason University, Arlington, VA 22201, USA
[c] Women in International Security, Washington, DC 20036, USA

ARTICLE INFO

Keywords:
Illicit supply chain
Counterfeit
Optimization
Disruption strategy

ABSTRACT

During the COVID-19 pandemic, millions of counterfeit respirators and fraudulent medical products infiltrated legitimate supply chains, often facilitated by registered businesses, third-party logistics providers, and companies in the technology sector. The trade in counterfeit respirators during the global health crisis threatened public health, safety, and security. The study uses seizure data, as well as analysis of shipping records and investigation reports to understand illicit supply chains of counterfeit N95 respirators. To compare the effectiveness of different types of disruption strategies, the authors propose a multi-period optimization problem and study different types of disruption strategies that would undermine counterfeit respirator supply chains. The authors also share numerical experiments and findings concerning the effectiveness of the proposed model.

1. Introduction

Counterfeiting is one of the most profitable crimes and the largest criminal enterprise in the world. Studies estimate the value of the global counterfeit market at over $500 billion per year [1]. U.S. Customs and Border Protection (CBP) and U.S. Immigration and Customs Enforcement (ICE)-Homeland Security Investigation (HSI) seized 19,522 shipments containing goods that violated Intellectual Property Rights (IPR) in Fiscal Year (FY) 2023, which equates to nearly 23 million counterfeit goods. The total estimated manufacturer's suggested retail price of the seized goods, had they been genuine, was over $2.76 billion (USD) [2].

But the impact of counterfeits goes beyond taking revenue away from legitimate economies. Counterfeiting also negatively impacts the job market. The National Association of Manufacturers "estimates that counterfeiting subtracted nearly $131 billion from the U.S. economy in 2019, including $22.3 billion in lost labor income and more than 325,500 fewer American jobs." [3].

In addition to their negative economic impacts, counterfeit products threaten safety and security [4] and counterfeit respirators pose particular harm to public health and safety as these substandard products fail to protect individuals from infection. The problem of counterfeit respirators became even worse during the COVID-19 pandemic as consumers rushed to purchase personal protective equipment (PPE) to protect them from infection. At times, the demand for respirators was ten times higher than global production capacity [5]. The problem was exacerbated by supply chain disruptions which caused significant shipping delays and prevented hospitals, medical workers, and others from obtaining the necessary and authentic PPE to protect employees' health and safety.

The surge in demand for COVID-19 related products led to increased need for manufacturing which many existing producers did not have the capacity to fulfill. Counterfeit producers took advantage of this rapidly increasing demand by registering new entities and shifting business operations to produce counterfeits that did not protect users. In the first two months of 2020 alone, almost 9,000 new Chinese manufacturers started producing masks according to the British Broadcasting Corporation (BBC) [6]. The mass-produced inferior respirators entered global supply chains on a massive scale. Over 59 million counterfeit 3 M masks were confiscated globally by August 2022. Many of these were seized at warehouses where as many as 1 to 2 million masks were confiscated at a time. Seizure rates of counterfeits range between 1 and 18 %, suggesting that there were hundreds of millions, if not billions, of counterfeit respirators in circulation [7]. Numerous conditions facilitated the entry of such a large number of counterfeit respirators into legitimate supply chains. Some authorized distributors unknowingly purchased and distributed counterfeit respirators while others did so knowingly. Certification of these illicit products by legitimate businesses and widespread spoofing of legal registered companies led to unintentional

☆ This article is part of a special issue entitled: 'Counter Illicit SC' published in Advanced Engineering Informatics.

* Corresponding author.
E-mail addresses: edwardhuang@auburn.edu (E. Huang), lshelley@gmu.edu (L. Shelley), laymay.19@gmail.com (L. Hashemi).

https://doi.org/10.1016/j.aei.2024.103084
Received 24 July 2024; Received in revised form 15 December 2024; Accepted 23 December 2024
Available online 28 December 2024
1474-0346/

purchase of counterfeits. For some, procurement of product trumped the desire for authenticity and reliability. Entry of counterfeit masks into major medical centers may have contributed to negative health consequences including personnel contracting COVID-19 [8].

The supply chain instability caused by the pandemic provided an opportunity for counterfeit producers to infiltrate legitimate supply chains, often facilitated by online advertisements [9]. Wholesalers frequently found it difficult to verify the legitimacy of their sources, as the products pictured online resembled authentic products. Rushed purchases resulted in reduced diligence in vetting suppliers, and the absence of authentic alternatives led many to unwittingly purchase counterfeits.

Another challenge was that because of low supply and high demand, many distributors paid more than the market price for respirators. "According to Nielsen Retail, the price of face masks increased by 319 % in the United States between end-of-January and end-of-February 2020" [4]. The shortages led many countries to introduce export restrictions to ensure that their citizens had access to quality masks which are essential to stopping the spread of disease [10]. These respirators were primarily intended for use by health care professionals (HCPs), individuals at greater risk of exposure to COVID-19. Unfortunately, in the United States, the CDC has reported that over 60 % of imported KN95 respirators (the quality needed by medical workers) were counterfeit [11]. Some reported defective products, upon analysis by the research team, shows that they were made only of tissue paper, thereby ensuring that they did not perform a protective function.

Although counterfeiting has been identified as an important problem by the OECD and by the US government [12], little is known in both practice and theory about the mechanisms and structure of counterfeit supply chains and the tactics of counterfeiters [13]. Furthermore, the need for a law enforcement response in different countries undermines the capacity of different agencies to respond quickly enough to deter the products from reaching markets [14]. Review of the existing illicit trade literature reveals that there is insufficient attention to counterfeits generally, and the extensive trade in counterfeit PPE and medical equipment has been largely ignored by academics. Anzoom *et al.* [15] reviewed studies on illicit supply chains published between 1980–2020 to provide a comprehensive overview of literature on supply chains and found only four papers on counterfeits. There has not been a significant growth in the literature since this survey article was published.

Isah *et al.* [16] propose a bipartite network model for inferring hidden ties between illicit actors and validate using case studies from the pharmaceutical sector. Other scholars study both licit and illicit supply chains, examining their relationships and comparing their operations and structures. González *et al.* [17] use a series of Variable State Resolution-Markov Chains (VSR-MC) to compare licit supply networks to illicit counterparts and identify locations where illicit activity is more prevalent. Ni et al. [18] propose the Relativistic Standard Generative Adversarial Network (RSGAN) and use currency counterfeiting as an example, training the model to distinguish between real and fake money using a Generative Adversarial Network. While these studies provide valuable insights into the operations of illicit supply chains, they do not examine the networks involved in specific types of illicit supply chains, such as counterfeit respirators.

One area that has received more attention is the problem of the entry of counterfeit medicines into supply chains. They pose serious threats to public health, leading researchers to develop and evaluate the effectiveness of disruption strategies such as the use of blockchain technology to trace active pharmaceutical ingredients (APIs) to identify counterfeit drugs [19]. The authors build upon existing research on illicit network dynamics from this and other areas of network analysis [20] and apply these insights to counterfeit PPE supply chain networks by developing a model that assumes actors seek to "optimize security through triadic closure, building trust, and protecting themselves and actors in close proximity through the use of brokers and offer access to the rest of the network" [21]. The study is also informed by research that examines the consequences of legal industries engaging in harmful activity [22]. We build upon these works to model an under-explored context, the role of legitimate businesses in facilitating the trade of counterfeit N95 respirators.

Examination of the literature on counterfeit trade reveals a gap in understanding the relationship between the legitimate and illegitimate companies that are part of these illicit supply chains. Some studies model counterfeit supply chains as only involving licit retailers [12]. Others focus on this as a problem that exists exclusively in the illicit economy. But as our research determined, the sale of counterfeit PPE was facilitated, in most cases, by a combination of both illicit and licit actors working together at different stages of the long and complex supply chain. There is a complex mixing of licit and illicit entities in counterfeit PPE supply chains. Our research suggests that any licit entity (ex. third-party logistics company, manufacturer, certification company, or supplier) can be abused to play a role in illicit supply chains. Our analysis found that the involvement of legally registered companies can be companies that might not know they are selling counterfeit goods because of deceptive advertising or certification processes (ex. bribing of certification companies for creation of false certificates). In contrast, some companies are engaged in willful blindness and facilitate the selling of counterfeits knowingly.

The authors summarize the business models observed from real world cases and use findings from the analysis of public and proprietary data to construct an optimization model to study counterfeit supply chains of N95 respirators. This article models a new problem, the growth and evolution of counterfeit respirator supply chains during the COVID-19 pandemic and presents possible disruption strategies. Using optimization models that detail the decisions of counterfeit producers, it evaluates the impact of various disruption strategies. The authors analyze the impact of targeting key nodes to significantly reduce the profits of counterfeiters. This evidence-based optimization approach, generalized from analysis of actual cases, allows for the development of effective detection and disruption strategies, allowing law enforcement, companies, governments, and other actors to prevent counterfeit and substandard products from entering legitimate supply chains.

The authors' research also challenges existing assumptions from studies on counterfeit supply chains. First, the research focuses on transnational trade and emphasizes the mixing of licit and illicit elements in counterfeit PPE supply chains. Second, the article analyzes online marketplace sales and publicly available data, expanding on a topic that only of recent interest in existing studies of counterfeiting [23]. Third, the authors model key intermediaries and facilitators such as shell companies and wholesalers. Finally, the authors offer recommendations for the most effective disruption strategies to counter the counterfeit PPE trade.

This study of counterfeit respirator supply chains consists of four components to model and understand illicit networks which can be applied to future investigations. First, the authors analyzed available cases of counterfeit 3 M N95 respirators and developed three counterfeit business models to understand the general structure and behavior of these illicit networks. Next, we develop a mathematical model based on the counterfeit business models to understand the whole illicit supply chain network. Third, we investigate and model different disruption strategies to determine which is most effective at which stage in the supply chain. Finally, real case studies are used to construct a numerical experiment that can support the selection of effective disruption strategies.

The article is organized as follows. Section 2 provides the problem description and overview. Sections 3 and 4 introduce the counterfeit model and disruption strategies respectively. Section 3 introduces three major business models observed in practice and corresponding mathematical counterfeit models. Section 4 explains five potential disruption strategies and presents a model of each strategy. Section 5 explains a case study and evaluates the effectiveness of different disruption strategies. Finally, Section 6 outlines findings from proposed optimization models and provides recommendations for effective disruption strategies.

2. Problem description

2.1. Problem overview

In this study, we focus on counterfeit producers seeking to maximize their profits and disruptors seeking to maximize their chance of detecting and confiscating counterfeit products. We model the supply chains of counterfeit N95 respirators as the competition between two stakeholders – counterfeit producers and disruptors (such as law enforcement or corporate anti-counterfeiting efforts). To model the actions of these stakeholders, a bilevel optimization model is developed to represent the adversarial relationship. Bilevel optimization was developed by Heinrich von Stackelberg et al. [24] to describe a leader–follower relationship where each level depends on each other, and the leader takes the follower's optimal reaction into account when making its decisions. Bilevel optimization is recognized as an important modeling tool since it allows the ability to formalize hierarchical decision processes [25]. Illicit networks are complex adaptive systems that learn from disruption strategies and subsequently change their operations to avoid detection [26]. Because counterfeit producers seek to maximize profit, they do not care whether they satisfy customers. Instead, they sell counterfeit products because it increases profits and often incurs limited risks for sellers and producers.

Despite the ability to gain significant profits, producers must also consider the costs associated with counterfeiting. To account for associated costs, the model includes two categories of expenditure – coordination costs and costs due to transaction risks. The former costs are related to building and maintaining network relationships with distributors, wholesalers, and other partners. The second category is associated with risk of detection of operations, seizure of products and equipment, or other forms of disruption [27]. To mitigate transaction cost risks, counterfeiters may invest in concealment, corruption, and evasion [28]. These efforts to avoid detection must be considered when developing and evaluating the impact of disruptions strategies. In the next section, the counterfeit model without applying any disruption strategy. Each disruption strategy and its corresponding constraints will be introduced in Section 4.

3. Counterfeit model

During the COVID-19 pandemic, the authors collaborated with 3 M and investigated more than one hundred cases of counterfeit N95 respirators, studying entire supply chains for counterfeits including intermediate international hubs as well as the locations of seizures on almost all continents. Analysis of counterfeit PPE supply chains reveals that they follow a similar structure, allowing us to make the following underlying assumptions for our models: (1) The main objective of all counterfeit producers is to maximize profit while minimizing risk of detection. Maximizing profits can be achieved by developing a large client base and gaining and maintaining the loyalty and trust of customers and key intermediaries such as logistics companies. Avoiding detection can be accomplished through efforts to obfuscate activity, preventing disruption and allowing counterfeiters to continue expanding their business and increase profits. Free trade zones are often used to obfuscate the movement of counterfeits [29]. (2) As observed from investigated cases, most shell companies (a shell company is an "incorporated company with no independent operations, significant assets, ongoing business activities, or employees" [30,31]) and wholesalers are located in an Asian city due to easy and cheap company registration and the accessibility of regional financial and logistics hubs as well as proximity to the factories that are a source of production of counterfeits. As a result, shell companies and wholesalers are assumed to be located in the same city; (3) The model accounts for contract and transport lead time between each node in the supply chain and it is assumed that inventory is overturned or updated each time period; (4) The inability to disrupt at the factory level is accounted for in the model as it is difficult to identify the specific factory location and there is often an unwillingness or inability of local authorities to disrupt production at the source.

In addition to the underlying assumptions, case investigations also provide the following insights: (1) Disrupting a counterfeit PPE supply chain does not imply the seizure of products at factories as in most cases, the seizure of goods at factories is not feasible. The inability to identify and disrupt factory production can be explained by several factors. First, counterfeiting is a transnational phenomenon, and cross border crimes are extremely difficult to detect and disrupt. Therefore, it is difficult to trace activities from source through transit countries and into destination markets. Many companies producing and selling counterfeit goods hide behind and work through legitimate companies to obfuscate their activity, preventing an understanding of the complete supply chain and also undermining efforts to develop an effective law enforcement response. A second and related reason for the difficulty in locating factories is that in some countries, state actors and law enforcement do not have sufficient incentive or resources to locate the producers. Moreover, corruption often undermines the effectiveness of the state response. As a result, disrupting such counterfeit supply chains should focus on the seizure of counterfeit products entering and distributed through legitimate supply chains. (2) In an attempt to hide their identity, counterfeiters establish shell companies or use wholesalers often located outside the U.S. due to easy and cheap company registration and the accessibility of regional financial and logistics hubs. (3) The business models of counterfeit PPE supply chains evolve over time. In the early stages of the pandemic, a B2C model was used to quickly reach customers. Later, counterfeiters switched to B2B models to attract distributors. In the third year, counterfeiters used both the B2B and B2C models to reach different types of customers. This represents a rapid evolution in counterfeit PPE business models where counterfeiters shift their behavior to maximize profits and minimize risk.

3.1. Types of business models

Three types of the counterfeit models are constructed based on real world investigations of counterfeit respirator supply chains.

3.1.1. Business model 1: Direct online (B2C Network)

First, we construct a model for a business to customer (B2C) network supply chain. See Fig. 1. In this model, the counterfeit producer uses a shell company that then sells products online. After the order is placed, the product is transported through a port or free trade zone and stored in a warehouse, ready to be shipped to the end user. In this most direct sale model, the business can retain nearly all the proceeds from counterfeit respirator sales, making this the most profitable of the three models.

3.1.2. Business model 2: Shell company to distributors (B2B Network)

In the second business model shown in Fig. 2, the counterfeiter uses online markets, platforms, and other technology to find distributors. Products are shipped through a shell company to a port and often through a free trade zone and then are stored in warehouses to be transported to distributors. The producer usually provides a discount to the distributor based on the high quantity of sale.

3.1.3. Business model 3: Wholesalers (Advanced B2B and B2C Network)

In the third business model shown in Fig. 3, the advanced B2B and B2C model, the counterfeit producer supplies products to a wholesaler. Next, the goods are transported through a port and possibly a free trade zone, transferred through a warehouse, and ultimately delivered to a distributor or end user. The producer must incentivize the wholesaler by sharing some of their profits. By using this approach, the producer avoids exposure and detection as only the wholesaler is exposed to

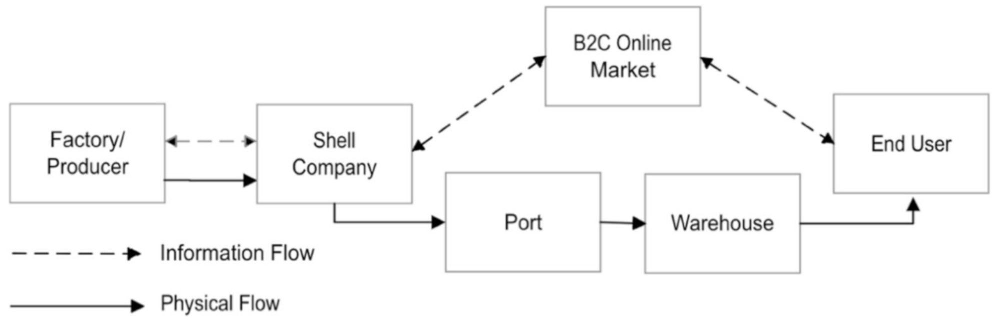

Fig. 1. Direct Online (B2C Network).

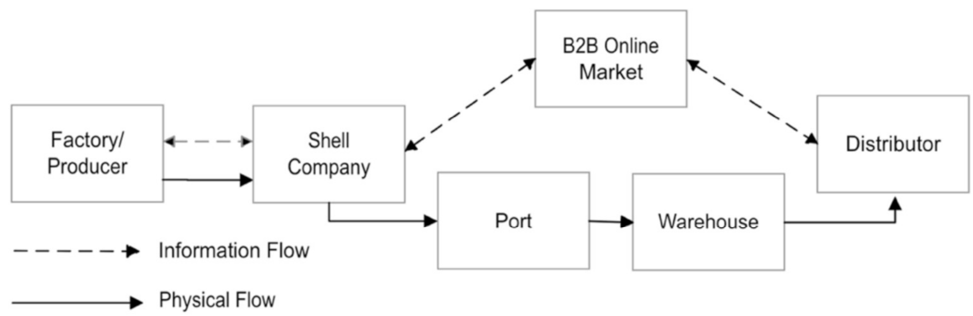

Fig. 2. Shell Company to Distributors (B2B Network).

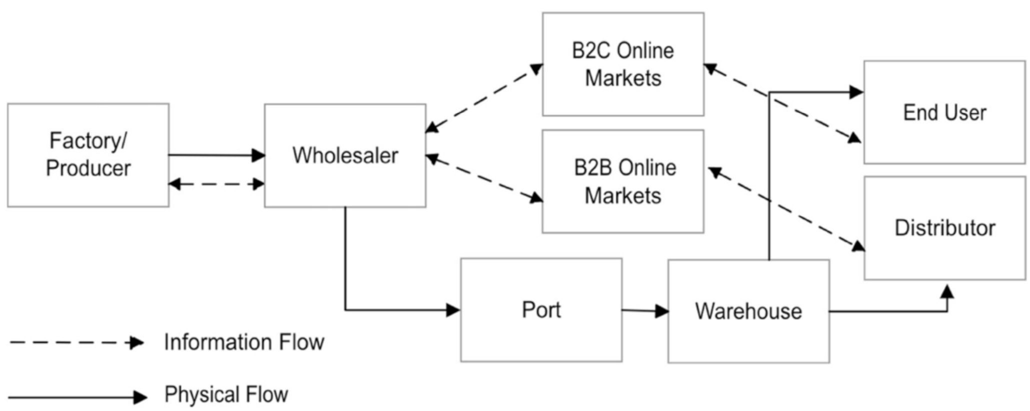

Fig. 3. Wholesalers (Advanced B2B Network).

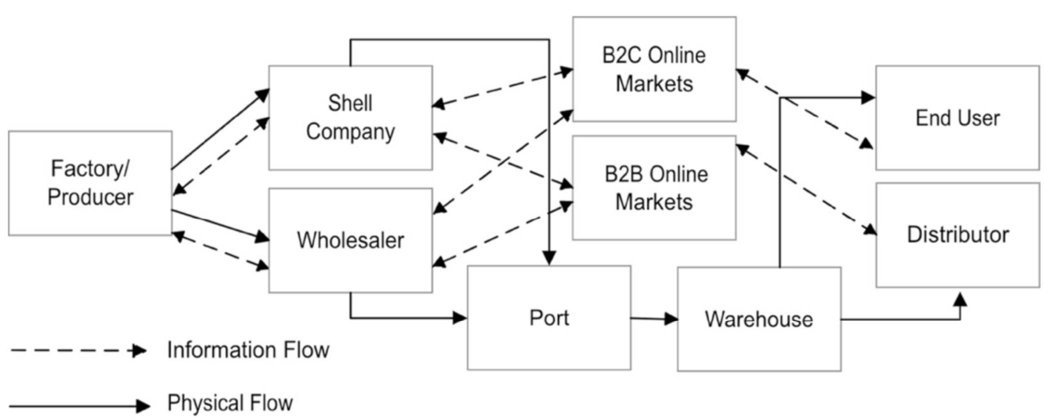

Fig. 4. Supply Chain Network Graph.

disruptors.

3.2. Counterfeit N95 supply chain network

All the above models are depicted in the supply chain network graph in Fig. 4 which provides an overview of physical and information flows.

Counterfeit producers change and adapt their business models to increase profits and minimize risk, often evolving rapidly. Although distribution through a wholesaler reduces a counterfeit producer's total gross profits, it also helps reduce the risk of detection. Alternatively, when perceived probability of detection is high, producers will establish shell companies and sell indirectly to retain more profit. Counterfeiters also determine if they will sell to end users (B2C) or distributors (B2B) based on demand and production capacity.

3.3. Mathematical Formulation

The counterfeit N95 supply chain shown in Fig. 4 is formulated as a mathematical model in this section. See Table 1.

Then, the counterfeit model without having any disruption strategy is formulated as follows.

$$\begin{aligned}\text{Max}\sum_{k,t} q_k\left(r^{dist}x_{k,t}^{B2B}+x_{k,t}^{B2C}\right)-\sum_t\Big(c^{ralc}\theta_t+c^{eps}u_t+c^{shell}w_t^{shell}+c^{whs}w_t^{whs}\\+c^{B2B}v_t^{B2B}+c^{B2C}v_t^{B2C}+c^{prod}x_t^{prod}+r^{whs}x_{h,t}^{store}\Big)\\-\sum_{w,t}c_w^{hold}x_{w,t}^{store}-\sum_{i,j,t}c_{i,j}^{ship}x_{i,j,t}^{ship}-\sum_w c_w^{fixed}y_w\\-g^{ralc}\sum_t\theta_t-g^{shell}\sum_t w_t^{shell}-g^{sale}\sum_{t,k}\left(x_{k,t}^{B2B}+x_{k,t}^{B2C}\right)\\-g^{ad}\sum_t\left(a^{B2B}v_t^{B2B}+a^{B2C}v_t^{B2C}\right)\end{aligned} \tag{1}$$

s.t.

$$z_t=\sum_{h=1}^{t}u_h,\forall t\in T \tag{2}$$

$$x_t^{prod}\le z_t,\forall t\in T \tag{3}$$

$$x_{k,t}^{B2B}\le a^{B2B}o_k^{B2B},v_{t-\bar{l}}^{B2B},\forall k\in K,\forall t\in T \tag{4}$$

$$x_{k,t}^{B2C}\le a^{B2C}o_k^{B2C}v_t^{B2C},\forall k\in K,\forall t\in T \tag{5}$$

$$x_{k,t}^{B2B}+x_{k,t}^{B2C}\le d_k,\forall k\in K,\forall t\in T \tag{6}$$

$$x_t^{prod}=\sum_{i\in\{s,h\}}x_{f,i,t}^{ship},\forall t\in T \tag{7}$$

$$x_{i,t}^{store}=x_{f,i,t-l_{f,i}}^{ship},\forall i\in\{s,h\},\forall t\in T \tag{8}$$

$$x_{i,t}^{store}=\sum\nolimits_p x_{i,p,t}^{ship},\ \forall i\in\{s,h\},\forall t\in T \tag{9}$$

$$\sum_{i\in\{s,h\}}x_{i,p,t-l_{i,p}}^{ship}=\sum\nolimits_w x_{p,w,t}^{ship},\forall p\in P,\forall t\in T \tag{10}$$

$$\begin{aligned}x_{w,t}^{store}+\sum\nolimits_k x_{w,k,t}^{ship}+\sum\nolimits_{j\in W-\{w\}}x_{w,j,t}^{ship}=\sum\nolimits_p x_{p,w,t-l_{p,w}}^{ship}\\+\sum\nolimits_{j\in W-\{w\}}x_{j,w,t-l_{j,w}}^{ship}+x_{w,t-1}^{store},\forall w\in W,\forall t\in T\end{aligned} \tag{11}$$

$$x_{k,t}^{B2B}+x_{k,t}^{B2C}=\sum\nolimits_w x_{w,k,t-l_{w,k}}^{ship},\forall k\in K,\forall t\in T \tag{12}$$

$$x_{s,t}^{store}\le M\bullet w_t^{shell},\forall t\in T \tag{13}$$

$$x_{h,t}^{store}\le M\bullet w_t^{whs},\forall t\in T \tag{14}$$

$$\sum\nolimits_{p,t}x_{p,w,t}^{ship}\le M\bullet y_w,\forall w\in W \tag{15}$$

$$\begin{aligned}\sum_k q_k\left(\sum_{h=1}^{t}r^{dist}x_{k,t}^{B2B}+x_{k,t}^{B2C}\right)-\sum_{h=1}^{t}\Big(c^{ralc}\theta_h+c^{exp}u_h+c^{shell}w_h^{shell}+c^{whs}w_h^{whs}\\+c^{B2B}v_h^{B2B}+c^{B2C}v_h^{B2C}+c^{prod}x_h^{prod}+r^{whs}x_h^{whs}\Big)\\-\sum_w\sum_{h=1}^{t}c_w^{hold}x_{w,h}^{store}-\sum_{i,j}\sum_{h=1}^{t}c_{i,j}^{ship}x_{i,j,h}^{ship}\\-\sum_w c_w^{fixed}y_w\ge\ddot{c}\forall t\in T\end{aligned} \tag{16}$$

$$\theta_t\in\{0,1\}\forall t\in T$$

$$y_w\in\{0,1\}\ \forall w\in W$$

$$z_t,x_t^{prod},x_t^{shell},x_t^{whs}\ge 0\forall t\in T$$

$$x_{w,t}^{store}\ge 0\ \forall w\in W,\forall t\in T$$

$$x_{k,t}^{B2B},\ x_{k,t}^{B2C}\ge 0\ \ \forall k\in K,\forall t\in T$$

$$x_{i,j,t}^{ship}\ge 0\ \forall i\in F,\forall j\in F\backslash\{i\},\forall t\in T$$

u_t, w_t^{shell}, w_t^{whs}, v_t^{B2B}, v_t^{B2C} are nonnegative integers $\forall t\in T$

The objective function (1) maximizes the total profit minus the risk measured by the money. Constraint (2) computes factory capacity. Constraint (3) guarantees that the goods produced at the factory cannot be more than the factory capacity. Constraints (4) and (5) are the B2B and B2C demand constraints, respectively. Constraint (6) is the maximum demand constraint of each city. Constraint (7) is the flow balance constraint of the factory. Constraints (8) and (9) are the flow balance constraints of the inbound and outbound flows of the shell company and wholesaler. Constraints (10) and (11) are the flow balance constraints of the ports, free trade zones and warehouses, respectively. Constraint (12) ensures that the selling quantity must be equal to the total shipping quantity from all warehouses. Constraints (13) to (15) guarantee that the shell company, wholesaler, and warehouse are used if it handles any counterfeit respirators, respectively. The counterfeit producer usually has a capital limitation, modeled in constraint (16).

4. Numerical results and disruption models

In this section, we investigate and model different disruption strategies to determine which is most effective to interrupt counterfeit respirator supply chains. Five disruption strategies can be employed to stifle counterfeit producer business growth and minimize future profits. This section outlines these disruption strategies to minimize the counterfeit producer's objective function.

Insights from collaboration with 3 M and other partners reveal the important role of disruption lead time on enforcement impact. The slow process of disrupting a supply chain provides counterfeiters a significant opportunity to make money after starting their businesses. Due to the vast number of resources and high level of coordination and communication necessary for implementing disruption strategies, some investigations can take months or years from identification to enforcement. Lead time is also impacted by the different civil and criminal laws in the jurisdiction of interest. One counterfeiting case in the United States took over one year to investigate and initiate enforcement action and many cases are still ongoing for damage recovery.

Given real-world complexities, only one disruption strategy is

Table 1
Summary of the notations.

Notation	Description
Indexes:	
m	Index for factory
s	Index for shell company
h	Index for wholesaler
Sets:	
T	Set of time periods, $t \in T$
P	Set of potential ports, $p \in P$
W	Set of potential warehouses, $w \in W$
K	Set of cities with PPE end users or distributors, $k \in K$
F	Set of all facility, $i,j \in F$ where $F = \{m\} \cup \{s\} \cup \{h\} \cup W \cup P \cup K$,
Parameters:	
$l_{i,j}$	Transportation lead time from facility i to facility j
$\tilde{l}$	B2B Contract lead time
d_k	Max demand of respirators per time period at city k
a^{B2B}, a^{B2C}	Number of B2B and B2C ads posted per person per time period, respectively
o_k^{B2B}, o_k^{B2C}	Order quantity attracted per ad on B2B and B2C websites at city k, respectively
c^{B2B}, c^{B2C}	Cost per employee posting on B2B and B2C websites per time period, respectively
c^{ralc}	Cost of factory reallocation
c^{prod}	Production cost per box
c_w^{fixed}	Fixed cost for using warehouse w
c^{shell}	Cost of operating a shell company per period
c^{whs}	Cost of having a wholesaler per period
c_w^{hold}	Warehouse inventory holding cost per time period at warehouse w
$c_{i,j}^{ship}$	Shipping cost from facility i to facility j
c^{eps}	Capacity expansion cost for any additional box
r^{whs}, r^{dist}	Price discount per box when selling to wholesalers and distributors, respectively
$\ddot{c}$	Minimum capital level of the counterfeiting company
q_k	Sell price at city k
g^{ralc}	Risk reduction of factory reallocation, $g^{ralc} \leq 0$
g^{shell}	Risk increasing of each shell company per period, $g^{shell} \geq 0$
g^{sale}	Risk associated with the sale quantity, $g^{sale} \geq 0$
g^{ad}	Risk associated with the online ads, $g^{ad} \geq 0$
M	A sufficiently large number (E.g. one may define $M = t\max c_t$)
Decision variables:	
x_t^{prod}	Number of boxes produced at time t
$x_{i,t}^{store}$	Number of boxes stored at facility i at time t
$x_{k,t}^{B2B}, x_{k,t}^{B2C}$	Sale quantity to B2B distributors and B2C end users at city k at time t, respectively
$x_{i,j,t}^{ship}$	Shipping quantity from facility i to facility j at time t
θ_t	1 if the counterfeit producer relocates their factory at time t, 0 otherwise
y_w	1 if the warehouse w is used, 0 otherwise
u_t	Capacity expansion of the factory at time t
z_t	Capacity of the factory at time t
w_t^{shell}, w_t^{whs}	Number of the shell companies and wholesales at time t, respectively
v_t^{B2B}, v_t^{B2C}	Number of the employees posting ads at B2B and B2C websites at time t, respectively

typically implemented at a time. Therefore, this research focuses on evaluating the effectiveness of each strategy rather than analyzing cost trade-offs between them. This approach helps disruptors prioritize strategies during investigations. Furthermore, each disruption strategy is analyzed individually by incorporating its corresponding decisions and constraints to assess its effectiveness.

4.1. Disruption strategy 1: Website takedown

Nearly all sales of counterfeit respirators are facilitated by online listings as sellers reach intended customers by advertising on ecommerce marketplaces, forums, social media, and websites [8]. Therefore, the first and least resource intensive strategy to limit counterfeit profits is to detect and disrupt online activity including advertisements, communications, and transactions. Online enforcement entails the identification and takedown of listings for counterfeit respirators. The removal of listings prevents producers from reaching consumers, thus negatively impacting profits. Online disruption strategies require little or no lead time. Most takedowns happen almost immediately (within 1–3 days of initial reporting). The associated costs of online enforcement are relatively low compared to other disruption strategies. Despite the advantages of this approach, there is relatively low probability that counterfeiters' profits can be completely disrupted through this strategy because sellers can quickly repost ads and reestablish online listings after they have been removed. A high percentage of website takedowns is necessary for effective disruption. But this can be difficult to achieve because vendors can always recreate or re-establish their business through alternative channels. This is observed through the common practice of vendors reemerging on platforms or marketplaces under a different vendor or seller ID after their website or account has been suspended or removed.

To model online enforcement and takedowns, the B2B and B2C website takedown rates will be used. Denote the B2B and B2C website takedown rates by r^{B2B} and r^{B2C}, respectively. Then, the counterfeit model considering the website takedown can be formulated by replacing constraints (4) and (5) with the following constraints:

$$x_{k,t}^{B2B} \leq \left(1 - r^{B2B}\right) a^{B2B} o_k^{B2B} v_{t-\tilde{l}}^{B2B}, \forall k \in K, \forall t \in T \ (4').$$

$$x_{k,t}^{B2C} \leq \left(1 - r^{B2C}\right) a^{B2C} o_k^{B2C} v_t^{B2C}. \forall k \in K, \forall t \in T \ (5').$$

Taking down or removing ecommerce listings and posts of counterfeit producers negatively impacts counterfeiter profits by reducing contact with potential buyers, exhausting resources needed to address the takedown and reestablish infrastructure and marketing. This enforcement also results in a loss of clients and a decline in trust from former and future customers through the posting of negative reviews and customer feedback online. Even in fragmented marketplaces, a loss of customer trust is a great concern for counterfeiters as well as for online sellers attempting to maintain quality control of their platforms. Although online marketplaces are often fragmented, many sellers use top platforms to reach the widest audience. Thus, sellers have a high incentive to maintain a trustworthy reputation on mature marketplaces through positive online ratings and feedback.

4.2. Disruption strategy 2: Wholesaler enforcement

A second disruption strategy is to interrupt the supply chain at the wholesale level by confiscating property at a physical location, often at the warehouses of wholesalers. Wholesalers help increase counterfeit producers' profits by advertising products, establishing relationships with customers, and assisting in logistics and distribution. Therefore, the interruption of wholesaler activities is expected to negatively impact producer profits. Like other disruption strategies, we must determine where to disrupt the wholesaler, what expenses are involved in enforcement, and if the target is worth targeting. Furthermore, it must be estimated whether there is a sufficient amount of goods to be seized to justify the use of law enforcement resources. Wholesaler seizures cannot be performed right away as they require investigation lead time. Enforcers must identify wholesalers associated with counterfeit producers which can take several months. With the wholesaler disruption strategy, detection often depends on the quantity being handled through the wholesaler. Investigators must also determine if wholesalers are actually selling counterfeit goods, another challenge that requires extensive time and resources as sales may not be of actual product but may instead be merely financial scams. Therefore, the costs associated with disrupting wholesaler activity is significantly higher than the costs associated with online enforcement.

The decision to raid a wholesaler is based on the quantity of goods sold in the previous time periods. Once the wholesaler processes more than a threshold value, referred to as the "quantity awareness", obtaining a search warrant to conduct a raid may be justified. To receive authorization, a high level of documentation must be provided to the courts and legal fees and travel for the corporation may be significant. Legal proceedings also increase "investigation lead time." The logic here is that up to a certain volume of counterfeit N95 respirators, i.e., quantity awareness, the producer is a "small fish" and although they are manufacturing and distributing counterfeits, the cost benefit analysis does not justify a raid. Investigations require gathering large amounts of evidence.

Denote the given quantity awareness of the wholesaler by $\ddot{x}^{whs}$, the given investigation lead time of the wholesaler by $\ddot{l}^{whs}$, and the seizure quantity of the wholesaler at time t by $\overline{x}_t^{whs}$. The counterfeit model with wholesaler enforcement is derived by replacing constraint (9) for wholesaler h with the following set of constraints:

$x_{h,t}^{store} = \sum_p x_{h,p,t}^{ship} + \overline{x}_t^{whs}$, $\forall t \in T$ (9′).

and adding a new constraint:

$$\text{if } \left(\overline{x}_t^{whs} \geq \ddot{x}^{whs}\right), \text{ then } \overline{x}_{t+\ddot{l}^{whs}}^{whs} \geq x_{i,t+\ddot{l}^{whs}}^{store}. \ \forall t \in T \tag{19}$$

Constraint (19) is not linear. To reformulate it as a linear constraint, the binary variables δ_t^{whs} representing the seizure of the wholesaler at time t is added and constraint (19) is replaced by:

$$x_{h,t}^{store} - \ddot{x}^{whs} \leq M \bullet \delta_{t+\ddot{l}^{whs}}^{whs}, \quad \forall t \in T \tag{20}$$

$$x_{h,t+\ddot{l}^{whs}}^{store} - \overline{x}_{t+\ddot{l}^{whs}}^{whs} \leq M \bullet \left(1 - \delta_{t+\ddot{l}^{whs}}^{whs}\right). \quad \forall t \in T \tag{21}$$

Counterfeit producers rely heavily on advertising and anonymity provided by wholesalers to maximize profits and minimize risk of detection. Because wholesalers often operate entirely separately from producers, it is likely that disrupting wholesaler activity will have little or no impact on producer profits. If a wholesaler's activity is disrupted, the producer loses profits associated with that wholesaler and must then spend resources to reestablish an alternative connection or relationship. However, other than the relatively low cost of reestablishing the lost partnership, the producer can simply shift to using alternative wholesalers without incurring significant loss of profit.

4.3. Disruption strategy 3: Shell company takedown

A third disruption strategy is to identify and take down shell companies associated with the counterfeit producer. This is key as it reduces the opportunity of the business to operate.

Denote the given quantity awareness of the shell company by $\ddot{x}^{shell}$, the given investigation lead time of the shell company by $\ddot{l}^{shell}$, the seizure quantity of the shell company at time t by $\overline{x}_t^{shell}$, and the binary variable representing the seizure of the shell company at time t by δ_t^{shell}. Then, the counterfeit model with the shell company takedown can be formulated by replacing constraint (9) for shell company s with the following constraint:

$x_{s,t}^{store} = \sum_p x_{s,p,t}^{ship} + \overline{x}_t^{shell}$. $\forall t \in T$ (9'').

and adding the following constraints:

$$x_{s,t}^{store} - \ddot{x}^{shell} \leq M \bullet \delta_{t+\ddot{l}^{shell}}^{shell} \quad \forall t \in T \tag{22}$$

$$x_{s,t+\ddot{l}^{shell}}^{store} - \overline{x}_{t+\ddot{l}^{shell}}^{shell} \leq M \bullet \left(1 - \delta_{t+\ddot{l}^{shell}}^{shell}\right) \ \forall t \in T \tag{23}$$

The takedown of a shell company is likely to have the least impact of all the disruption strategies. Similar to the takedown of wholesalers, the original producer can easily establish a replacement shell company at little expense. After a shell company is taken down, the business may also be less inclined to establish additional shell companies or partake in expansion strategies for fear of further detection or disruption. Generally, disrupting at the shell company level has little impact on counterfeit producer profits as explained in section 5.3.3.

4.4. Disruption strategy 4: Warehouse seizure

Another physical disruption strategy is to seize counterfeit goods at a warehouse. While warehouse seizures can be extremely effective at reducing counterfeiter profits, there are several obstacles countering the ability of enforcement agencies to carry out warehouse raids including limited resources, knowledge constraints, and the high degree of proof needed to obtain a search warrant of private property from a judge. Costs are high because rightsholders in the United States must prepare and provide extensive documentation to convince a judge that there are counterfeits present in a warehouse. In addition, they may need to retain legal counsel and incur travel costs associated with presenting evidence to a court that a particular facility may contain counterfeits. Lead time for a court hearing depends on the quantity of suspected counterfeit goods and the ability to identify warehouses containing counterfeits, which is often challenging and time consuming. Even if these costs are incurred by the brand owner to get the counterfeits seized, there is a possibility that the owners of the counterfeits may relocate goods in the period prior to the raid being authorized. Similar to the wholesaler disruption strategy, this option would only be implemented by a company owning a brand that suspects very significant violations of its trademark or at a specific quantity threshold or quantity awareness.

Denote the given quantity awareness of a warehouse w by $\ddot{x}_w^{ws}$, the given investigation lead time for the warehouse by $\ddot{l}^{ws}$, the seizure quantity of a warehouse at time t by $\overline{x}_{w,t}^{ws}$, and the binary variable representing the seizure of the shell company at time t by $\delta_{w,t}^{ws}$. Then, the counterfeit model with the warehouse seizure can be formulated by replacing constraint (15) with the following constraint:

$x_{w,t}^{store} + \sum_k x_{w,k,t}^{ship} + \sum_{j\in W-\{w\}} x_{w,j,t}^{ship} + \overline{x}_{w,t}^{ws} = \sum_p x_{p,w,t-l_{p,w}}^{ship} + \sum_{j\in W-\{w\}} x_{j,w,t-l_{j,w}}^{ship} + x_{w,t-1}^{store}$, $\forall w \in W, \forall t \in T$(15′).

and adding the following constraints:

$$\sum_p x_{p,w,t-l_{p,w}}^{ship} + \sum_{j\in W-\{w\}} x_{j,w,t-l_{j,w}}^{ship} + x_{w,t-1}^{store} - \ddot{x}_w^{ws} \leq M \bullet \delta_{w,t+\ddot{l}^{ws}}^{ws}, \ \forall w \in W, \forall t \in T \tag{24}$$

$$\sum_p x_{p,w,t-l_{p,w}+\ddot{l}^{ws}}^{ship} + \sum_{j\in W-\{w\}} x_{j,w,t-l_{j,w}+\ddot{l}^{ws}}^{ship} + x_{w,t-1+\ddot{l}^{ws}}^{store} - \overline{x}_{w,t+\ddot{l}^{ws}}^{ws} \leq M\left(1 - \delta_{w,t+\ddot{l}^{ws}}^{ws}\right), \ \forall w \in W, \forall t \in T. \tag{25}$$

While seizure of products at a warehouse is resource intensive, it is also the disruption strategy with the greatest potential to minimize counterfeiter profits. When a warehouse seizure is successfully conducted, the company selling counterfeits loses all goods at that location along with the associated revenue. The exposure of counterfeiting operations and associated civil and possible criminal actions *may* negatively impact the producer's finances and reputation. If other businesses learn of government intervention, it may make other businesses (wholesalers, logistics companies, financial institutions, and distributors) less likely to do business with the counterfeiter, negatively impacting their profits.

4.5. Disruption strategy 5: Customs seizure

Customs seizures can be another effective disruption strategy as confiscating counterfeit products while in transit can help address the complex and transnational nature of the trade. Training customs and other officials on the development and implementation of disruption strategies can stem the growth and profits of counterfeit producers in ports, airports and free trade zones. These strategies require resources and training that facilitate customs officials' ability to distinguish between authentic and counterfeit products.

To model customs training and seizure, we denote the given custom seizure rate by r^{cus}. Then, the counterfeit model considering customs training and seizure can be formulated by replacing constraint (14) with the following constraint:

$$(1 - r^{cus}) \bullet \left(x^{ship}_{h,p,t-l_{h,p}} + x^{ship}_{s,p,t-l_{s,p}}\right) = \sum\nolimits_{w} x^{ship}_{p,w,t}, \forall p \in P, \forall t \in T \quad (14')$$

Customs seizures have a direct impact on the physical flow of illicit goods. In many cases, all goods identified as counterfeit are destroyed (as is the case in the United States), preventing these illicit and potentially harmful products from entering legitimate supply chains.

4.6. Case study and numerical experiment

In this section, we present the case study and apply the proposed model to analyze the effectiveness of each disruption strategy. In Section 5.1, we describe the data collection and implementation details. In Section 5.2, we show the counterfeit model without applying any

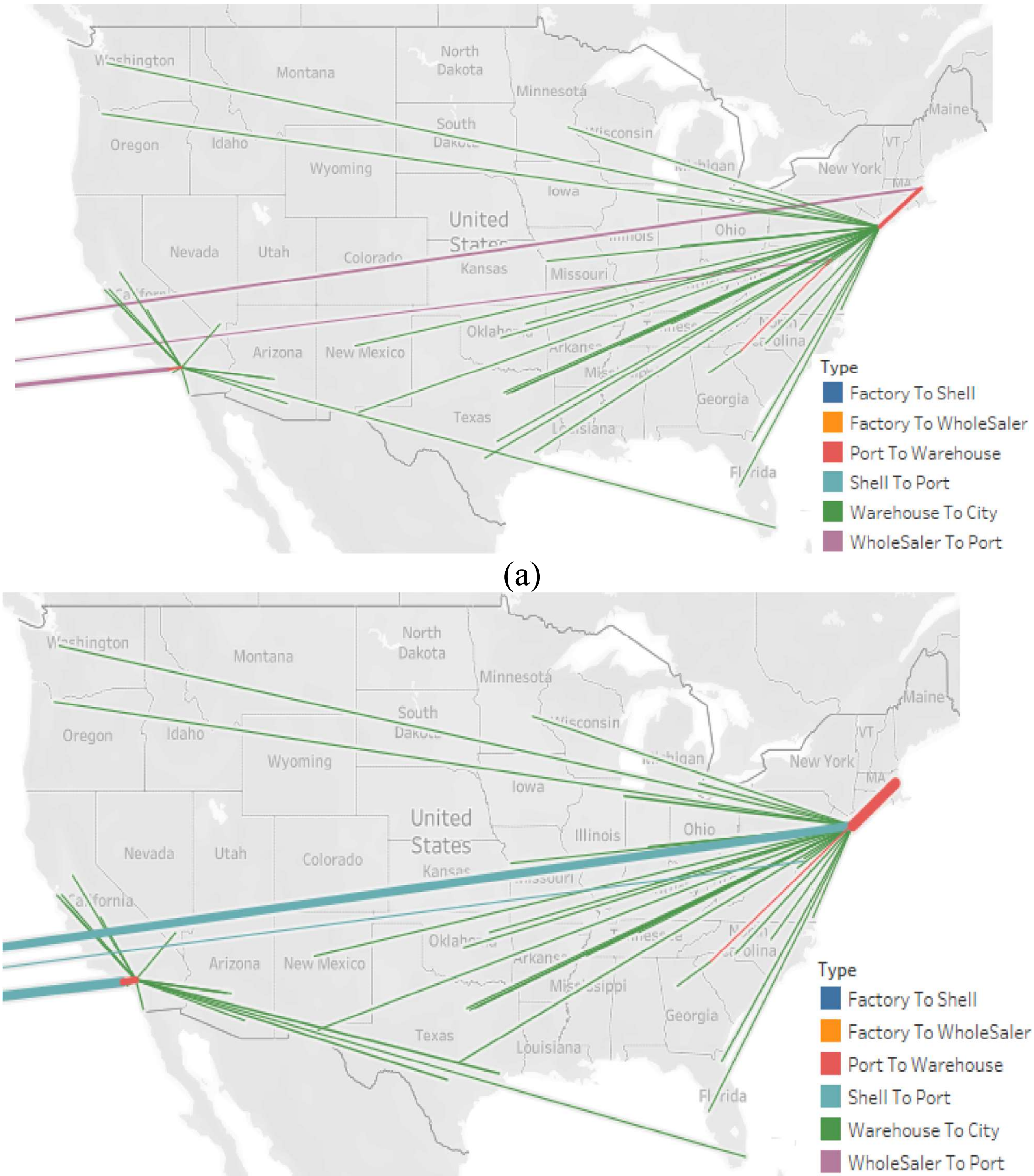

Fig. 5. (a) Supply Chain Base Model at T = 1. (b) Supply Chain Base Model at T = 19.

disruption strategy, which is called the base model. In Section 5.3, each disruption strategy is applied, and the sensitivity analysis of each disruption is reported. Section 5.4 summarizes the overall findings and provides recommendations.

4.6.1. Data collection

Insights on counterfeit PPE supply chains are based on analyzing real cases assembled from the public–private partnership and collaboration with 3 M as well as public and corporate data to determine how counterfeit respirators were transported and how these fraudulent products entered legitimate supply chains. Four primary sources of data were analyzed to examine counterfeit PPE supply chains: corporate hotline and investigations data; customs and seizures reports; investigative case files and business registry records; and publicly available or open-source data including but not limited to information from social media and ecommerce marketplaces. Many counterfeits were initially identified through hotlines established by 3 M for customers to report on the inferior quality of products, helping to specify the infiltration of counterfeits into legitimate supply chains. Hundreds of customs, seizures, and investigation reports were analyzed to identify individuals and companies suspected of fraud, financial crimes, and production and/or distribution of counterfeit respirators. Examined documents included seizures notices from customs agencies and relevant case files including invoices, bills of lading, purchase orders, and court documents. Corporate registries were used to investigate companies involved in counterfeiting.

To complement the analysis of customs, seizures and investigative reports, the authors also analyzed cyber activity by investigating publicly available information on counterfeit products sold through standalone websites, sales platforms, marketplaces, and social media. This data was used to construct models of counterfeit supply chains by analyzing related shipping, invoice, and other financial records. Data on destinations of illicit respirators were also analyzed where available. Case files were used to identify warehouse and other transit locations used by counterfeiters as well as the respirator demand for each city. Once key supply chain routes and locations were identified, the authors used information from major transportation companies to determine shipping costs and transportation lead times.

Through joint investigations with 3 M, it was determined that most counterfeit respirators are produced outside the U.S. and transported to major cities and ports in the U.S. The states with the highest number of seizures include New York (New York JFK and Queens), California (Los Angeles), and Maine (Portland). The quantity of respirators seized at these entry locations are quite high, often ranging from a few hundred thousand to several million. After entering ports of entry, products are distributed through warehouses and third-party logistics companies to end users throughout the country. Based on evidence from illicit supply chain research, the model includes the location of ports, warehouses, and major cities within the United States. Ports and warehouse locations were gathered based on where seizures took place during the pandemic. City locations were identified by determining the most populous cities in the United States, thus those locations with the highest demand for respirators. The proposed optimization model was implemented through C# in Microsoft Visual Studio 2019. Gurobi 9.5.0 is used for optimization. The system configuration is Windows 11, 64 bits, 16 GB Ram and Intel Core 7–9700 K 3.60 GHz Processor.

4.6.2. Base model

The base model is the counterfeit model without disruption, and thus represents how the counterfeit producers' business evolves without any intervention. Base model results depicted in Fig. 5 lead to several important findings. First, counterfeit producers will expand facilities and production capability when there is sufficient money and resources to do so. Expansion of production capabilities only happens in the first few months, a similar pattern to the cases observed during the pandemic. Examination of base model results over time reveals companies will focus on B2C sales in earlier periods and later switch to B2B trade. This can be seen through increased use of warehouses and shell companies over time as shown in Fig. 5(a) and 5(b). In Fig. 5(a), with the base model at $T = 1$, a wholesaler is used to distribute product to end customers through B2C channels. While in Fig. 5(b) with the base model at $T = 19$, there is use of a shell company by the counterfeit producer. This is largely to increase the scale of sales and subsequently, to maximize profit.

4.6.3. Disruption strategies

Counterfeit producers learn and adapt their behavior quickly to avoid detection and interference. Thus, it is important to identify which disruptions strategies are most effective at various points in the supply chain. From the mathematical models of disruption strategies outlined in Section 4, we found that disruption strategies that target earlier points in the supply chain (further upstream) are most effective. The following section outlines disruption model results and the impact of each disruption strategy on producer profits.

4.6.4. Disruption strategy – website takedown

Fig. 6 shows the impact of B2B and B2C website takedowns on counterfeit producer profits. The x and z axis represent the percentage of B2C and B2B website takedowns while the y axis represents the percentage of profit when compared to the base model, or the percentage of profit retained by the counterfeiter. The colors in the figure legend and graph represent the range of percent of profit relative to the total profit earned in the base model. Based on the model results, counterfeiter profits are only reduced by approximately 10 % when over 50 % of websites are taken down for both B2B and B2C models.

The mathematical model results for disrupting counterfeit respirator production through online enforcement demonstrate that this approach can be an effective disruption strategy to minimize counterfeit producer profits. However, as shown in Fig. 6, online enforcement only has a significant negative impact on producer profits if 90 % or more of B2C advertisements and 80 % of B2B advertisements are removed respectively. Thus, B2B website takedowns are more effective than B2C takedowns and both strategies are only effective if they target a large percentage (80 % or more) of advertisements.

4.6.5. Disruption strategy – wholesaler seizure

Table 2 shows the effectiveness of intercepting counterfeit supply chains through seizure of goods at the wholesale level. The columns represent quantity awareness, while the rows represent investigation lead time, both as defined in Section 4.2. The percentages in each column and row represent the amount of profit retained by the counterfeit producer at each combination of lead time and quantity awareness. As seen by the retention of 100 % profit in all scenarios in Table 2, seizures from wholesalers have little to no impact on producer profits. This is because counterfeiters can quickly switch to alternative wholesalers or shell companies when one avenue is blocked. The model results suggest this that wholesaler seizure is not an effective disruption strategy. This result can be explained by the fact that wholesalers are often an entirely different corporate entity than the producer, making it difficult to trace wholesaler activity back to the manufacturer. Also, wholesalers have already paid for the purchase and have little chance of recovering costs from the producers or distributor. Distributing counterfeit respirators through wholesalers allows counterfeiters to hide their identity while also retaining the most profit even if one of their wholesalers is captured.

4.6.6. Disruption strategy – shell company enforcement

Based on the results of the takedown of a shell company shown in Table 3, there is little impact of a shell company takedown on counterfeit producer profits. The maximum reduction in profits is less than 14 % with zero lead time. It is unlikely that a shell company could be seized with zero lead time given the extensive resources and time needed to collect evidence and conduct an investigation. Thus, the 13.5

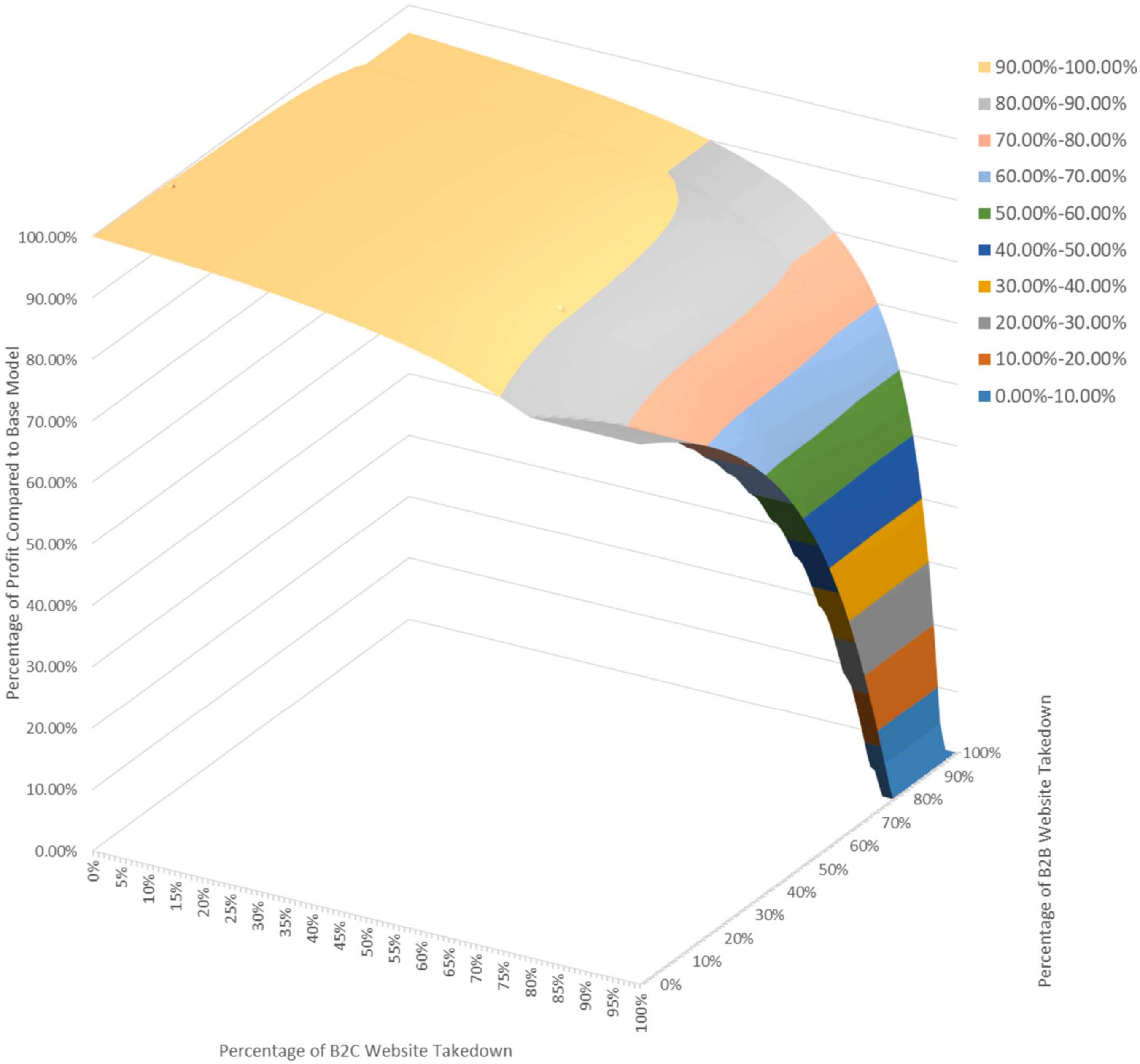

Fig. 6. Contour Graph of B2B and B2C Takedowns.

Table 2
Impact of Wholesaler Seizure.

Profit Percentage		Quantity Awareness				
		1000	2000	3000	4000	5000
Investigation Leadtime	0	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %
	1	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %
	2	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %
	3	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %
	4	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %
	5	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %

% reduction at a quantity awareness of 1000 and investigation lead time of 0 is highly improbable.

Across all quantities of awareness and investigation lead times, profit is only reduced by 0.5 to 13.5 %, showing this disruption strategy results in little impact.

Even when shell company enforcement can occur quickly, counterfeit producers still manage to protect their profits. With a lead time of one month and a quantity awareness of 1000, the counterfeiter producer still retains 91.78 % of its profits. With a lead time of 2 months and a quantity awareness of 2,000, the counterfeiter only loses approximately

Table 3
Impact of Shell Company Enforcement.

Profit Percentage		Quantity Awareness				
		1000	2000	3000	4000	5000
Investigation Leadtime	0	86.50 %	92.06 %	95.38 %	97.23 %	99.09 %
	1	91.78 %	94.67 %	95.92 %	97.58 %	99.17 %
	2	92.31 %	94.18 %	96.56 %	97.92 %	99.25 %
	3	92.38 %	95.13 %	96.82 %	98.10 %	99.33 %
	4	93.02 %	94.37 %	97.25 %	98.27 %	99.42 %
	5	93.41 %	95.96 %	97.35 %	98.27 %	99.50 %

Table 4
Impact of Wholesaler and Shell Company Seizure.

Profit Percentage		Quantity Awareness				
		1000	2000	3000	4000	5000
Investigation Leadtime	0	41.41 %	82.34 %	94.21 %	96.74 %	98.70 %
	1	91.78 %	93.22 %	95.50 %	96.91 %	98.79 %
	2	92.22 %	94.04 %	95.70 %	97.08 %	98.87 %
	3	92.45 %	93.87 %	95.97 %	97.42 %	98.98 %
	4	92.93 %	94.58 %	96.40 %	98.01 %	99.04 %
	5	93.41 %	95.86 %	97.22 %	97.83 %	99.12 %

6 % of their original profits. The longer the investigation lead time, the less the impact on producer profit. Thus, while shell company seizures have more impact on producer profits than enforcement against wholesalers, the overall effect is negligible, especially given the long lead times necessary for this disruption strategy.

4.6.7. Disruption strategy – wholesaler and shell company seizure

Another possible disruption strategy is to combine both wholesaler and shell company seizure by targeting both nodes in the supply chain at the same time. As shown in Table 4, the combination of wholesaler and shell company seizure has significantly more impact on counterfeiter profits than implementing either disruption strategy individually. With no lead time (row 1), producer profit can be reduced by almost 59 %. At a quantity awareness of 2,000 and an investigation lead time of 1 month, profits are reduced by over 6 %. These results demonstrate the important role of lead time. When lead time is more than 1 month, the counterfeit producer has the opportunity to adapt their strategy to reduce risk of detection and disruption. The ability of counterfeiters to quickly learn from and adapt to disruption strategies explains why most profits are retained after seizures with longer investigation lead times.

4.6.8. Disruption strategy – warehouse seizures

The results of warehouse seizures in Table 5 show the effectiveness of this strategy to prevent counterfeit goods from entering legitimate supply chains as they have a significant impact on counterfeiter profits when implemented in early stages and in cases with smaller quantities. As demonstrated in row one, with no lead time warehouse seizures can reduce counterfeiter profit by 0.39–1.90 % for a quantity awareness of 3,000 or less. For a quantity awareness of 4,000 or higher, warehouse seizures have no impact on profits. Warehouse seizures can be an effective disruption strategy for time periods involving smaller quantities (less than 4,000).

Based on the reduced impact on producer profit as lead time increases, the results demonstrate that disruptions that take place in the early stages, or upstream, of the supply chain, i.e., wholesalers and shell companies, are more effective than warehouse seizures which take place in the later stages of the supply chain after products have been delivered to warehouses for delivery to end users or distributors. This explains why warehouse seizures have less impact on profits than wholesaler and shell company takedowns. This can also be explained by the fact that there is a lower number of shell companies whereas producers can ship products to many warehouses. Thus, it is easier to pinpoint shell companies versus dispersed warehouses located more downstream in the supply chain.

4.6.9. Disruption strategy – customs seizures

Another common disruption strategy is to seize counterfeit goods at ports of entry and transport locations. This enforcement action is usually implemented by customs officials. The impact of customs seizures on counterfeit N95 respirator profits is shown in Fig. 7. Based on the model results, if customs successfully seize more than 24 % of counterfeit goods, producers will have no incentive to continue operations as their business activity and revenue is completely disrupted (profit percentage compared to the base model drops to 0 %). Based on the model results, any percentage increase in the custom seizure rate can have a strong impact on counterfeiters' profit. Additionally, customs seizures can be an extremely effective strategy to completely disrupt counterfeit respirator supply chain networks if seizure rates can be increased to 24 % or higher. This is why enhancing vigilance in Free Trade Zones is key as the OECD has pointed out [26].

4.7. Overall findings of numerical experiments

Our numerical experiment led us to several findings. First, customs seizures are an effective intervention that can be implemented through awareness raising programs, collaboration between customs and brand protection divisions of companies, and the allocation of more resources to increase detection rates. Next, regarding website takedowns, B2B interruptions are more effective than B2C disruptions, but in order to be effective more than 80–90 % of the listings must be taken down. Third, if the wholesaler or shell company is seized, counterfeit producers will simply switch to using alternative shell companies or wholesalers. A more effective strategy is to seize both wholesaler and shell companies. As seen in Table 4, profits can be reduced by as much as 58 % when combining these disruption strategies as compared to simply seizing the wholesaler or shell company where there is little impact on profits (Table 2), demonstrating the effectiveness of combining disruption strategies. Model results also led to two more general findings. First, investigation lead time is a very important factor for enforcement impact (Tables 2-5). Second, intercepting counterfeits earlier or farther up in the supply chain is a more effective disruption strategy as it has larger impact on producer profits.

Table 5
Impact of Warehouse Seizures.

Profit Percentage		Quantity Awareness				
		1000	2000	3000	4000	5000
Investigation Leadtime	0	98.10 %	99.52 %	99.69 %	100.00 %	100.00 %
	1	98.22 %	99.52 %	99.69 %	100.00 %	100.00 %
	2	98.65 %	99.54 %	99.69 %	100.00 %	100.00 %
	3	99.00 %	99.54 %	99.69 %	100.00 %	100.00 %
	4	99.04 %	99.69 %	100.00 %	100.00 %	100.00 %
	5	99.05 %	99.69 %	100.00 %	100.00 %	100.00 %

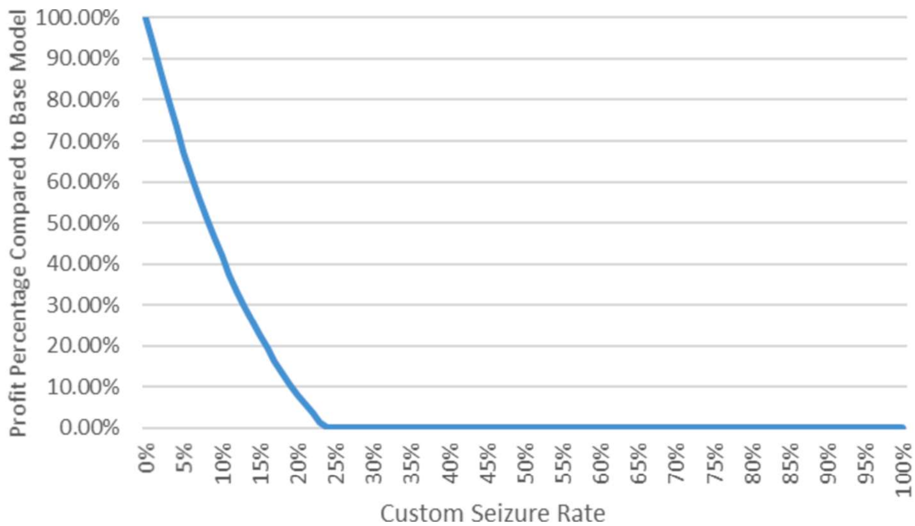

Fig. 7. Customs Seizure Impact on Producer Profit.

5. Conclusion

Analysis of a new and high impact form of counterfeiting, the production of counterfeit medical-grade respirators during the pandemic, not only contributes to existing research regarding the sale of fake medical products but can also help address public health concerns surrounding illicit supply chains for other products that are harmful to health. The current study provides insights gained from the authors' yearlong public–private partnership with 3 M and the sharing of proprietary corporate data. This data combined with advanced data analytics allowed more in-depth analysis of the dynamics of counterfeiting than existing literature or previous studies. Moreover, the scale of counterfeiting medical masks during the pandemic was on such a significant level and evolved so rapidly that it was possible to test models using very significant data sets.

In this paper we summarize three types of counterfeit N95 respirator supply chains (B2C. B2B. and advanced B2B) observed during the COVID-19 pandemic and model the supply chain as a bilevel multi-period optimization problem that considers both counterfeiters' and disruptors' decisions. Five disruption strategies that would counteract counterfeit respirator supply chains are modeled and evaluated including: website takedowns, wholesaler seizure, enforcement against shell companies, warehouse seizures, and customs seizures.

A key finding of the research is that counterfeit PPE supply chains are often complex and counterfeit producers constantly shift their behavior in response to disruption strategies to avoid detection. There is a mixing of illicit and licit activity which necessitates the development of novel disruption strategies as proposed here.

The study shows the ability of a bilevel optimization model to develop effective disruption strategies and reveals the importance of investigation lead time. Our findings demonstrate the benefits of seizing counterfeits early and systematically in the supply chain. This approach results in total, rather than partial, disruption of counterfeit networks by targeting whole layers of the supply chain. This demonstrates a need to understand the whole supply chain, not just individual nodes. Without this holistic perspective, counterfeiters can easily shift or adapt their strategies to continue activity despite disruption. Monitoring all counterfeit activities throughout the supply chain ensures that producers cannot re-establish operations after disruption.

As the pandemic progressed, detecting and disrupting counterfeit respirator supply chains and other illicit supply chains, particularly of medical and health products, is more critical. Success in countering counterfeits can be best achieved through preventative measures targeting counterfeit products upstream and seizing them as close to the source as possible. It is also important to investigate illicit supply chains using a multidisciplinary approach that incorporates skills and information from various sectors. This includes the use of artificial intelligence (AI), network analysis, advanced data analytics, analysis of sophisticated commercial packages, as well as domain and corporate registries. Also, an understanding of the operational patterns of illicit actors is key. These patterns are influence by cultural and historic patterns of trade, its geographic dimensions and the forces driving it within different economies. Additionally, understanding trade patterns in the countries of production and along the international supply chain is essential. Public-private partnerships are crucial for raising public awareness of the issue and supporting timely, impactful research with data needed to understand and concretely address the problem of illicit trade in counterfeits.

CRediT authorship contribution statement

Edward Huang: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Louise Shelley:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Layla Hashemi:** Writing – original draft, Validation, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research work was supported by the National Science Foundation in the United States under Award D-ISN-2039779: Collaborative Research: An Interdisciplinary Approach to Understanding, Modeling, and Disrupting Drug and Counterfeit Illicit Supply Chains. The research for this article was made possible by a data sharing agreement and partnership between 3M, Legit Script, and George Mason University (GMU).

Data availability

The authors do not have permission to share data.

References

[1] OECD Organisation for Economic Co-operation and Development (OECD)/ European Union Intellectual Property Office (EUIPO) (2022). Dangerous Fakes: Trade in Counterfeit Goods that Pose Health, Safety and Environmental Risks, Illicit Trade, OECD Publishing, Paris, https://doi.org/10.1787/117e352b-en.

[2] U.S. Customs and Border Protection (2023). Intellectual Property Rights Seizure Statistics. Available at: https://www.cbp.gov/sites/default/files/2024-06/ipr-seizure-stats-fy23-508.pdf.

[3] NAM. *NAM Leads Fight Against Counterfeits During COVID-19 Pandemic* (2020). Available at: https://www.nam.org/nam-leads-fight-against-counterfeits-during-covid-19-pandemic-9909/.

[4] OECD Organisation for Economic Co-operation and Development (OECD) (2019). Trade in Fake Goods Is Now 3.3% of World Trade and Rising, Organisation for Economic Co-operation and Development (2019). Available at: https://www.oecd.org/newsroom/trade-in-fake-goods-is-now-33-of-world-trade-and-rising.htm.

[5] Organisation for Economic Co-operation and Development (OECD) (2020). The Face Mask Global Value Chain in the COVID-19 Outbreak: Evidence and Policy Lessons, Organisation for Economic Co-operation and Development. Available at: https://www.oecd.org/coronavirus/policy-responses/the-face-mask-global-value-chain-in-the-covid-19-outbreak-evidence-and-policy-lessons-a4df866d/.

[6] British Broadcasting Corporation (BBC). (2020). Coronavirus: French police seize 140,000 black market masks. Available at: https://www.bbc.com/news/world-europe-52430738.

[7] Organisation for Economic Co-operation and Development (OECD). (2018). Governance Frameworks to Counter Illicit Trade. https://doi.org/10.1787/9789264291652-en.

[8] E. Proffitt. (2020) The dangers of fake PPE. *BDJ Team*. 2020;7(8):20–1. doi: 10.1038/s41407-020-0399-5. Epub 2020 Sep 18. PMCID: PMC7499936.

[9] J.P. Kennedy, M. Rorie, M.L. Benson, COVID-19 Frauds: An Exploratory Study of Victimization during a Global Crisis, Criminol. & Public Policy 20 (3) (2021) 493–543, https://doi.org/10.1111/1745-9133.12554.

[10] J. Howard, A. Huang, Z. Li, Z. Tufekci, V. Zdimal, H. M. van der Westhuizen, A. W. Rimoin. An evidence review of face masks against COVID-19, In: Proceedings of the National Academy of Sciences, 118(4) (2021).

[11] Centers for Disease Control and Prevention (CDC). (2022) Types of Masks and Respirators. Available at: https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/types-of-masks.html.

[12] OECD Organisation for Economic Co-operation and Development (OECD)/ European Union Intellectual Property Office (EUIPO) (2021), Global Trade in Fakes: A Worrying Threat, Illicit Trade, OECD Publishing, Paris, https://doi.org/10.1787/74c81154-en.

[13] T. Staake, F. Thiesse, E. Fleisch, The emergence of counterfeit trade: a literature review, Europ. J. of Mark. 43 (3/4) (2009) 320–349, https://doi.org/10.1108/03090560910935451.

[14] K. Kammel, M. Azim-Kramer, D. Duquet, L. Patterson, Trademark counterfeiting enforcement beyond borders: the complexities of enforcing trademark rights extraterritorially in a global marketplace with territorial-based enforcement, Fordham Intell. Prop. Media Ent. LJ 33 (2023) 595.

[15] R. Anzoom, R. Nagi, C. Vogiatzis, A review of research in illicit supply-chain networks and new directions to thwart them, IISE Trans. 54 (2) (2021) 134–158.

[16] H. Isah, D. Neagu, D., P. Trundle.Bipartite network model for inferring hidden ties in crime data. In: Proceedings of the 2015 IEEE/ACM international conference on advances in social networks analysis and mining 2015 (2015) 994-1001.

[17] J.Á. González Ordiano, L. Finn, A. Winterlich, G. Moloney, S. Simske, On the analysis of illicit supply networks using variable state resolution-markov chains, in: International Conference on Information Processing and Management of Uncertainty in Knowledge-Based Systems, Springer, Cham, 2020, pp. 513–527, https://doi.org/10.1007/978-3-030-50146-4_38.

[18] F. Ni, Z. He, S. Jiang, W. Wang, J. Zhang, A generative adversarial learning strategy for enhanced lightweight crack delineation networks, Adv. Eng. Informatics 52 (2022) 101575, https://doi.org/10.1016/j.aei.2022.101575.

[19] R. Kumar, T. Rakesh, Traceability of Counterfeit Medicine Supply Chain through Blockchain, in: 2019 11th International Conference on Communication Systems & Networks (COMSNETS), IEEE, Bengaluru, India, 2019, pp. 568–570, https://doi.org/10.1109/COMSNETS.2019.8711418.

[20] C. Morselli (Ed.), Crime and Networks, Routledge, New York and London, 2014.

[21] D. Bright, J. Koskinen, A. Malm, Illicit network dynamics: the formation and evolution of a drug trafficking network, J. of Quant. Criminol. 35 (2) (2019) 237–258.

[22] N. Passas, N. R. Goodwin. *It's Legal but It Ain't Right: Harmful Social Consequences of Legal Industries*. Evolving Values for a Capitalist World. Ann Arbor: University of Michigan Press (2004).

[23] OECD Organisation for Economic Co-operation and Development (OECD)/ European Union Intellectual Property Office (EUIPO) (2021), Misuse of E–Commerce for Trade in Counterfeits, OECD Publishing, Paris, Available at: https://www.oecd.org/content/dam/oecd/en/publications/reports/2021/10/misuse-of-e-commerce-for-trade-in-counterfeits_dfd7df43/1c04a64e-en.pdf.

[24] H. Von Stackelberg, et al., *Market structure and equilibrium*, Springer Science & Business Media, 2010.

[25] T. Kleinert, M. Labbé, I. Ljubić, M. Schmidt, A survey on mixed-integer programming techniques in bilevel optimization, EURO J. on Comput. Optim. 9 (2021) 100007.

[26] P.A.C. Duijn, P.M. Sloot, From Data to Disruption. Digital Investing. 15 (2015) 39–45.

[27] E.K. Clemons, S.P. Reddi, M.C. Row, The impact of information technology on the organization of economic activity: the "move to the middle" hypothesis, J. Manag. Inf. Syst. 10 (2) (1993) 9–35.

[28] G. Basu, Concealment, corruption, and evasion: a transaction cost and case analysis of illicit supply chain activity, J. of Transp. Secur. 7 (3) (2014) 209–226.

[29] OECD Organisation for Economic Co-operation and Development (OECD)/ European Union Intellectual Property Office (EUIPO) (2018), Trade in Counterfeit Goods and Free Trade Zones, OECD Publishing, Paris, Available at: https://www.oecd.org/content/dam/oecd/en/publications/reports/2018/03/trade-in-counterfeit-goods-and-free-trade-zones_g1g893a6/9789264289550-en.pdf.

[30] FATF – Egmont Group. Concealment of Beneficial Ownership, FATF (2018). Available at: www.fatf-gafi.org/publications/methodandtrends/documents/concealment-beneficial-ownership.html.

[31] I.V. Floros, T.R. Sapp, Shell games: on the value of shell companies, J. of Corp. Finance 17 (4) (2011) 850–867.