Resilient Supply Chain Operations Following Major Disturbances: Lessons from COVID-19 Cases

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Abstract: Resilience has become a major concern to the global supply chain after the COVID-19 pandemic. Although the pandemic is hopefully tailing off, this study remains essential for future preparedness against major disruptions in global supply chain operations. This paper extends the Public-Health Corridors (PHC) concept from international travel coordination to global supply chain operations, with the underlying goals of reopening borders and alleviating social and financial burdens. Very little has been learnt from and very few guidelines are provided for developing PHC that recovers supply chain operations. This research fills this research gap by providing the architecture of PHC. Game-theoretical models with a strategic government-private-public-partnerships (G3P) mechanism are proposed to demonstrate how effective PHC can establish a new norm for social and economic activities under COVID-19 with minimal additional burdens. It offers theoretical evidence for possible approaches that facilitate effective stakeholder collaboration in launching PHC. Findings show that the implementation of basic PHC can resume supply chain operations through appropriate PHC measures and investments, while a well-designed G3P mechanism significantly bridges the gap between new norms and pre-pandemic conditions. A targeted subsidy program is crucial for profitability, and well-crafted contracts are essential for achieving Pareto improvement and reducing required subsidies.

Keywords: SDG 17: Partnerships for the Goals; Resilient Supply Chain; Public Health Corridor (PHC); Government-Private-Public-Partnerships (G3P); Contract-based Coordination

I. INTRODUCTION

Supply chain operators are facing greater challenges than ever because the types and numbers of threats that can disrupt a supply chain are increasing (Mensah & Merkuryev, 2014; Pandey et al., 2023; Saleheen & Habib, 2022), such as natural disasters, terrorism, trade wars, etc. This research considers the urgent problem that the COVID-19 pandemic has dramatically undermined supply chain

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operations. Although COVID-19 is hopefully tailing off, this study is still timely and crucial for mankind to get better prepared for dealing with major disturbance events during global supply chain operations in the future. The present study takes the post-COVID-19 pandemic as an example to craft solutions to supply chain disruptions produced by a major disturbance.

Many countries have restricted cross-border transportation, which leads to social and economic loss (Bastani et al., 2021; Ku et al., 2021; Rosik et al., 2022). Scientists and regulators argue that global supply chain operations have been found as channels of COVID-19 transmissions (Lewis, 2021a; Lupu & Tiganasu, 2022; Pang et al., 2020). Although some researchers remain sceptical, specialists cannot rule out the possibility of virus transmission through supply chain operations. The Centers for Disease Control and Prevention (CDC), the World Health Organization (WHO), and health agencies recommend people clean and disinfect surfaces of objects. Moreover, cleaning surfaces is easier than improving ventilation, and global sales of surface disinfectants totalled US$4.5 billion by the end of 2020 (Lewis, 2021b). There is no doubt that it is inadequate and burdensome to fight the COVID-19 pandemic by one country or business alone since our world economy and society are interconnected by global supply chains. The International Civil Aviation Organization (ICAO) recently provided a concept of Public Health Corridors (PHC) in the aviation recovery plan to prevent COVID-19 from spreading through air travellers (ICAO, 2020). This research extends this PHC concept for freight logistics as the healthy and safe re-connections amongst countries, within which people and/or objects can freely travel and trade across borders under the pandemic, see Figure 1. The launch of PHC is a public good and entails the collective efforts of all the stakeholders, and this research is among the first attempts of theoretical research into effectively building the global supply chain PHC through contract-based government-private-public partnerships (G3P) during the COVID-19 crisis.

Global supply chains are faced with a dilemma: On one hand, the COVID-19 virus spreads across borders through global supply chain operations. The ignorance or relaxation in implementing inspections on imported objects and/or overseas travellers has led to resurging clusters in many cities. On the other hand, strict restrictions and border closures severely affect the economy as well as the well-beings of individuals and communities. They inevitably disrupt business activities and communications amongst countries and impose hardships on individuals and communities, while their corresponding gains were proven short-lived without combining other measures (Khan et al., 2022; Mallapaty, 2020). The research objective is to find out an optimal solution for the global supply chain dilemma by using a contract-based healthy supply chain corridor (HSCC) model, with a long-term goal of opening up borders without compromising public health risks as soon as possible.

The global supply chains have witnessed massive disruption and continue to grapple with the adversity of COVID-19. Surveys by the Institute for Supply Management (ISM) reveal that nearly 75% of businesses report supply chain disruption due to COVID-19-related restrictions (Institute for Supply Management (ISM), 2020a). Unfortunately, some of them cannot handle this kind of disruption with China, in which supply chain members tighten the screening (Institute for Supply Management (ISM), 2020b). Obviously, global supply chains are faced with a great challenge and a lengthy recovery to normal operations in the wake of the COVID-19 outbreaks (Rozhkov et al., 2022). The establishment of PHC can be considered a must and cure for the operational continuity of the global economy.

This research takes advantage of the PHC concept from ICAO and applies the lessons of successful experience in dealing with supply chain crises, aiming to build healthy corridors for freight logistics as soon as possible and then to form a new norm. Global supply chain security has become a major concern since the 9/11 attack in 2001, after which the supply chain is regarded as a potential channel of weapons of mass destruction and terrorist acts (Waller et al., 2008). Supply chain disruptions resulting from the closures of port and border crossings led to devastating economic impacts (Lee & Whang, 2005). Besides terrorist attacks, Autry and Bobbitt (2008) said that numerous catastrophic events have adversely affected supply chain security, like earthquakes, hurricanes, etc., and they investigated a firm-level construct to mitigate security breaches. The supply chain crisis at that time performed very similarly to what our world is facing now. Organizations should create supply chain security as a priority through investing in secure activities with security efforts (Williams et al., 2009).

Therefore, we propose a global supply chain PHC considering the G3P among supply chain members, third-party agencies, government, individuals and communities, see Figure 1. The PHC concept is based on the use of "healthy" goods, "healthy" people, and "healthy" equipment and environment, which "healthy" referring to implementing consistent and appropriate measures to ensure virus-free status, to the extent possible. Specifically, goods refer to the objects and their associated packages, cases, pallets and containers during production, packaging, and transportation processes, and COVID-19 negative labels are attached to "healthy" goods; people consist of the staff, workers, drivers, and all other related personnel inside the global supply chain, and "healthy" people hold a COVID-19 negative report for successive operations; equipment and environment include the workplaces, facilities, and vehicles, etc, and rectification is required without a "healthy" label, which may lead to work stoppages. Businesses should adhere to PHC regulations, while third-party agencies will provide COVID-19 testing and inspection services. The freights with COVID-19 negative reports and labels will achieve healthy certificates so authorities have the confidence to freely allow freights to enter borders. Furthermore, the advanced PHC will be launched with a strategic G3P mechanism where each player demonstrates considerable effort and success in COVID-19 prevention. G3P strategies, including contract-based coordination, subsidy schemes, negotiation and intervention, will be proposed to establish a highly coordinated PHC, which brings the performance of new norms of global supply chain operations formed through PHC closer to that of the norm. The implementation of the global supply chain PHC faces the following questions:

(1) what role does each stakeholder play in the effective launch of PHC for the global supply chain?
(2) how will a strategic G3P mechanism function to coordinate healthy supply chain operations?
(3) How close are new norms of the global supply chain formed through PHC to the norm before?

These questions will be answered by developing a novel game-theoretic HSCC model of contract-based government-private-public partnerships aiming to recover global supply chain operations from the adversity of COVID-19. Research evidence exhibits a high possibility of COVID-19 transmission via cold chain transportation (Hu et al., 2021; Lewis, 2021a). Ensuring public health within the food chain requires stringent measures at each stage of production, handling, and transportation (Gonzalez et al., 2021). Additionally, detecting the COVID-19 virus on objects is harder and more complicated than that in vivo; therefore, this research takes the cold chain as an example for model formulation and analyses. To simplify calculations, we assume a three-stage supply chain consists of an exporter like suppliers and manufacturers, a logistics service provider, and an importer that serves customers. By using the right management approach, policy guidance, and operational processes, the global supply chain PHC will effectively function for the smooth flow of objects and individuals during the COVID-19 crisis. However, few research works have discussed the approaches to the potential disruptions of global supply chain operations. Rizou et al. (2020) summarized the possible transmission ways of COVID-19 through food supply chains and highlighted the need for analytical tools for supply chain safety. Guan et al. (2020) analysed the supply chain effects of a set of idealized lockdown scenarios and concluded that resulted in disruptions incur devastating losses. Raj et al. (2022) developed a conceptual framework to investigate supply chain challenges and the corresponding mitigation strategies during the post-COVID-19 crisis. Previous researchers and experts focus on the COVID-19 impacts on supply chains and highlighted the need for a solution to end COVID-19 transmission through global supply chains with minimal additional burdens (Aday & Aday, 2020; Remko, 2020; Sarkis, 2020). This research fills the research gap by building a global supply chain PHC with a well-designed G3P mechanism and demonstrates how will this PHC function for recovering supply chain operations to near-normal with a novel game-theoretic model. It contributes to the following aspects:

(1) It proposes a novel theoretical framework of global supply chain PHC through contract-based government-public-private partnerships (G3P) to form new norms for supply chain operations during the COVID-19 crisis, which fills the research gap and enriches the practical guidelines.

(2) It develops a game-theoretic HSCC model combining Pareto-efficient coordination settings to theoretically explore an optimal solution for the existing supply chain disruptions through game equilibrium and equilibrium boundaries.

(3) Successful partnerships achievable through contracts and strategic actions jointly undertaken by all the stakeholders are discovered, and theoretical and numerical findings are used to derive and formulate policy and managerial implications at the strategic and operational levels.

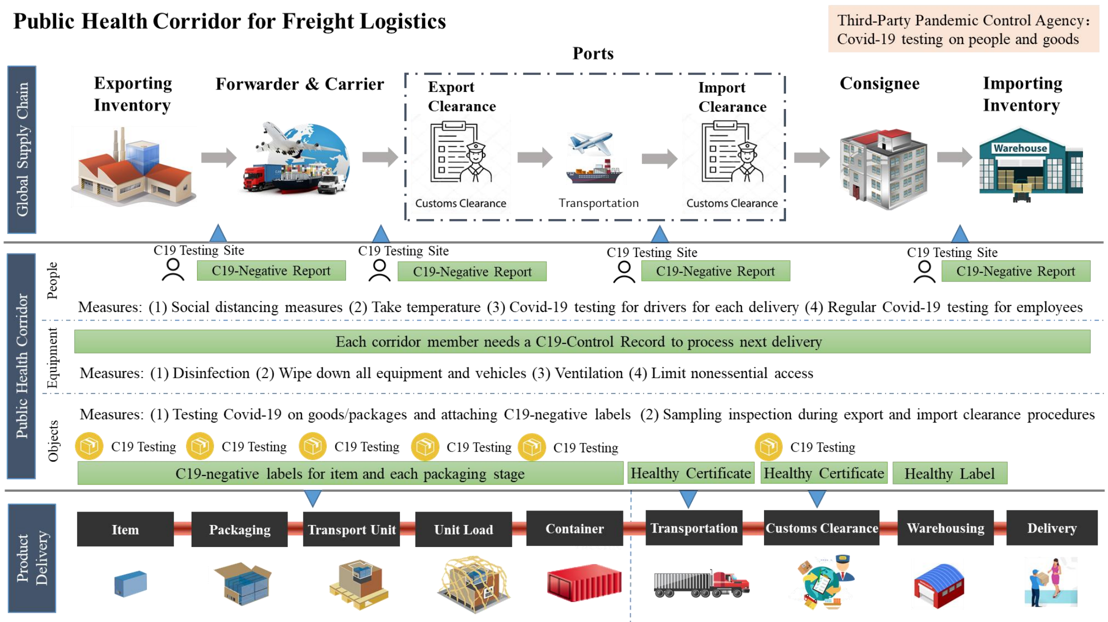

Figure 1. Public Health Corridor for Freight Logistics

Alt Text: PHC architecture considering product delivery, PHC, and supply chain structures

II. LITERATURE REVIEW

This literature study briefly reviews the previous literature to identify the theoretical bases for model development and the existing research gaps that this research aims to address.

2.1 Supply Chain Resilience during COVID-19

The concept of supply chain resilience has emerged in literature since the early 2000s and gained significant attention following the COVID-19 pandemic in 2019. Researchers identified two main factors, which drive the application of resilience to supply chain management: an increasingly turbulent business environment and inadequate risk management measures (Pettit et al., 2019). It still lacks consensus about the definition of supply chain resilience (Alvarenga et al., 2023). Some scholars define resilience as the ability to manage disruptions and their aftermath, while others include the preparation period before a disruption (Tukamuhabwa et al., 2015). Ivanov and Das (2020) examined the impacts of COVID-19 outbreaks on supply chain resilience and analyzed mitigation measures and potential recovery paths. Alvarenga et al. (2023) leveraged digital technology to improve supply chain resilience and robustness. Shen and Sun (2023) conducted an empirical analysis to strengthen supply chain resilience during the COVID-19 pandemic, and took JD.com as an example to implement supply chains and intelligent platforms. Ivanov (2024a) explored the optimal post-pandemic recovery strategies through a discrete-event simulation model. Although considerable research has taken into consideration theoretical approaches to supply chain resilience associated with COVID-19, most studies focus on only one aspect: preparation, response, or recovery (Birkel et al., 2023; Ivanov, 2024b; Ivanov & Keskin, 2023; Li et al. 2023; Van Oorschot et al., 2023;). Ivanov et al. (2023) conducted a comprehensive review of the existing literature on supply chain viability, yet studies employing game theory remain limited. Recent empirical research has explored strategies to prepare for, respond to, and recover from disruption (Daghar et al. 2023; Zhao et al. 2024), but theoretical studies have yet to provide integrated frameworks covering all three phases.

This research contributes to the literature by using game-theoretical models to comprehensively address all aspects of supply chain resilience. It aims not only to respond to or recover from supply chain disruptions out of the COVID-19 pandemic but also to prepare for potential future disruptions through building public health corridors. Moreover, the majority of recent studies on supply chain recovery during COVID-19 focus on one or two supply chain players (Gupta et al., 2021; Ivanov & Dolgui, 2020; Moosavi et al., 2022). Literature on multi-player supply chain management to address COVID-19 disruptions remains scarce, especially considering cross-border transportation. This research fills these research gaps by introducing public health corridors in a three-tier supply chain to achieve preparation, response, and recovery of normal operations during the COVID-19 pandemic.

2.2 Supply Chain Disruption and Measures

Supply chain disruption refers to any event or series of events that occur suddenly and interrupt the normal flow of goods and services within a supply chain. Such disruptions can arise from a variety of sources, including natural disasters (Song et al., 2018) such as storms, earthquakes, floods etc., pandemics like COVID-19 (Pujawan & Bah, 2022), terrorist attacks (Lee & Whang, 2005), logistic problems (Dupont et al., 2018), production issues (Yang et al., 2017), political instability (Kanike, 2023), technological failures (Ivanov et al., 2019), and so on. They pose significant challenges to the continuity and efficiency of supply chain operations. Supply chain players, therefore, should implement effective and robust methods to successfully prepare for, respond to, or recover from a supply chain disruption (Katsaliaki et al., 2022). Disruptions out of pandemics have attracted increasing academic attention. Extensive literature has discussed supply chain disruptions, which further proposes various frameworks and strategies for resilience. The most commonly used methodologies for achieving resilience to address supply chain disruptions include improved demand forecasting (Swierczek & Szozda, 2019), better partnership among supply chain members (Wakolbinger & Cruz, 2011), joint relationship efforts (Li et al., 2015), synchronized decision-making (Sakti et al., 2023), resilient design of supply chain (Rezapour et al., 2017), investment in resilience

(Bakshi & Kleindorfer, 2009), risk assessment and management (Katsaliaki et al., 2022). While extensive research presents various resilience strategies, there is a lack of theoretical studies with integrated measures for cross-border disruptions during pandemics. This research tries to design PHC for cross-border supply chains through better partnerships with investment strategies to address disruptions under an uncertain market.

Shortly after COVID-19 was declared a pandemic, agencies like the CDC, WHO, and FDA recommended control measures to reduce the risk of SARS-CoV-2 transmission (Ezzatpanah et al., 2022; WHO, 2020). These measures protect against both direct and indirect contact with the virus but lead to supply chain disruptions due to border closures and disinfection protocols during import and export processes. Additionally, firms and industries face substantial financial burdens when implementing these control measures, alongside regulatory policies, and thus this makes strategic solutions urgently needed to alleviate this pressure. The WHO previously recommended a five-level classification for control measures based on their intensity and complexity during implementation (WHO, 2021). This research takes advantage of this classification to define the PHC efforts of a firm that aims at enhancing customers' confidence in public health.

2.3 Public-Private Partnership and Coordination

Public-private partnership (P3) has gained popularity over many years and has been defined as an innovative and long-term cooperation between public and private sectors to achieve specific goals or objectives, under which resources are placed and risks are proportionately shared (Fandel et al., 2012). P3 can be organised optimally if each partner focuses on their core competencies, which enables the most efficient service delivery through diverse collaboration with its counterparts. Industry-wide government regulations compensate for firm control with financial or police support, under which supply chain members prioritize the advantages offered by government programs (Siddiq et al., 2022). Correspondingly, many scholars have explored the ability of P3 to achieve resilience when major disturbances occur in supply chain operations. Stewart et al. (2009) leveraged public-private partnerships to improve community resilience facing disasters, and Voss and Williams (2013) extended it to encourage supply chain partners to voluntarily improve their security. Similar works from Busch and Givens (2013), Gebhardt et al. (2022), and Drakaki et al. (2023) provide incentives through public-private partnerships. Inspired by previous works, we extend the concept of P3 into government-private-public partnerships (G3P). This approach targets the interaction between regulatory bodies and supply chain members alongside the public to achieve a collaborative response to and recovery from COVID-19 disturbances and better preparation for the potential further supply chain disruptions.

Contracts are widely regarded as one of the most effective mechanisms for creating partnership incentives due to their desirable features (Wang et al., 2024b). These agreements facilitate clear expectations and responsibilities, which foster trust and collaboration among partners. Many contracts have been provided to guide the supply chain resilience against potential disruptions (Hosseini-Motlagh et al., 2023; Wakolbinger & Cruz, 2011). They offer a well-organized method for managing risks, ensuring that all parties are ready to respond effectively to unexpected events. Besides, subsidy programs also act as a useful tool for designing partnerships. Subsidies provide financial support and incentives that further strengthen collaborative efforts and enhance overall resilience (Guo et al., 2019; Guo et al., 2021; Wang et al., 2024a). Hence, this research combines contracts and PHC subsidies to form a G3P partnership with the underlying goals of mitigating disruptions and reducing social and financial burdens.

2.4 Brief Summary

The COVID-19 pandemic has exposed critical vulnerabilities in global supply chains, which prompts widespread research into supply chain resilience. However, much of theoretical research has focused on isolated aspects, such as preparation, response, or recovery, without a holistic approach that integrates all three phases. This study addresses this research gap by introducing a game-theoretical framework that encompasses preparation, response, and recovery, specifically through the creation of PHC within a three-tier supply chain.

Additionally, this research expands on existing models by incorporating cross-border dynamics and multi-player involvement, areas that have been largely overlooked in prior studies. The introduction of PHC offers a structured approach to mitigating the disruptions caused by the COVID-19 pandemic and preparing for dealing with future crises. Although measures have been implemented, there is no ready answer to effectively resume supply chain operations through integrated measures while ensuring public health. This research leverages the WHO five-level classification of control measures to define the PHC efforts of a firm that aims at enhancing customers' confidence in public health. The PHC is designed to strengthen supply chain partnerships for addressing disruptions, taking into account demand uncertainty and PHC investment.

Furthermore, this study innovatively extends the traditional public-private partnership (P3) model into a government-private-public partnership (G3P). This collaborative approach unites regulatory bodies, supply chain members, and the public to create a strategic interaction to supply chain disruptions. Through well-designed contracts and PHC subsidies, the study emphasizes the importance of aligning incentives across all stakeholders to reduce both social and financial burdens while maintaining operational continuity.

All in all, the novelty of this research lies in coordinating a three-tier supply chain to ensure preparation, response, and recovery during disruptions through the implementation of PHC. Few guidelines exist for developing PHC to recover supply chain operations, creating a significant knowledge gap. This research addresses this urgent issue by proposing strategies to maintain normal social and economic activities with minimal additional burdens during disruptions. Several contracts and PHC subsidies are suggested to form partnerships, aligning with control measures proposed by regulatory bodies and agencies. Table A1 summarizes recent publications to identify theoretical bases and highlight research gaps, which emphasizes the novelty and contributions of this study (See Appendix).

III. MODEL FORMULATION AND PROBLEM SOLVING

This section attempts to build a strategic HSCC model considering contract-based government-private-public partnerships (G3P), which form global supply chain public health corridors between two or more countries/regions that would recover healthy and smooth global supply chain operations.

3.1 Model Description

The proposed HSCC model classifies supply chain stakeholders into three players: Player 1 refers to the exporter, including suppliers and manufacturers, and Player 2 represents the logistics service provider, including forwarders and carriers, ports, etc. Player 3 is the importer that serves the end customers. Under the PHC, goods must be reported COVID-19 negative before entering borders. Hence, either Player 1 or 2 is required to conduct PHC measures for achieving COVID-19 negative labels of imported goods. From Figure 2, two scenarios exist for obtaining labels: (1) goods are attached COVID-19 negative labels by exporting enterprises (Player 1) along with production and packaging processes; (2) logistic services provider (Player 2) conducts PHC measures and attach COVID-19 negative labels if goods are delivered to ports without labels. Scenario (2) incurs higher PHC costs and time costs than scenario (1) as Player 2 has to unpack goods for COVID-19 testing, attach labels, and then repackage goods. Besides supply chain members, other PHC stakeholders, like third-party agencies, government and communities, are considered. The third-party agencies provide technical support and services on PHC measures, like COVID-19 testing and inspection. PHC subsidy budgets from the government and communities mainly cover all domestic enterprises.

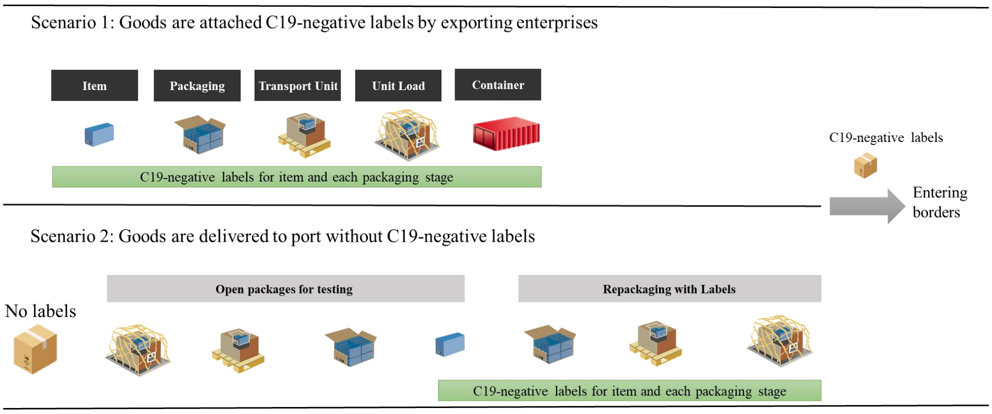

Figure 2. Two scenarios for COVID-19 negative requirements before entering borders

Alt Text: Scenario 1 costs less than Scenario 2 since Scenario 2 needs to unpack goods for COVID-19 testing, attach labels and then repackage goods

This research explores effective solutions to maintain the operational continuity of cross-border supply chains during the COVID-19 crisis. The supply chain is usually decentralized where all the players make decisions for their own interests. It inevitably sacrifices the holistic benefit of the supply chain that would be achieved from integrated decision-making (Wang & Choi, 2020c). Moreover, the PHC health requirements burden players with extra costs. Coordination among these supply chain insiders would likely contribute to healthy performance and desirable profitability. The integrated supply chain acts as an idealised benchmark, in which all the players make decisions as a group with a central decision-maker. Hence, mathematical models considering decentralized, integrated, and coordinated supply chains are built, where the Stackelberg game and Lagrange optimization methods are used to solve the PHC decision-making problem. The notations of the demand function, parameters, and decision variables are described in Table 1.

Table 1. Notations for the proposed HSCC model

Notations for Demand Function			
$D(i_b,i_m,i_s,p,\varepsilon)$	The stochastic and differentiable demand function. $D(i_b,i_m,i_s,p,\varepsilon)=y(i_b,i_m,i_s,p)+\varepsilon$.	ε	The random variable for the demand uncertainty, $E(\varepsilon)=\mu$.
$y(i_b,i_m,i_s,p)$	The deterministic demand function, $y(i_b,i_m,i_s,p)=a+b_b\cdot i_b+b_m\cdot(i_s+i_m)-ep$.	i_b	The PHC efforts of Player 3, which are assumed to be a continuous decision variable.
i_m	The PHC efforts of Player 2, which are assumed to be a continuous decision variable.	i_s	The PHC efforts of Player 1, which are assumed to be a continuous decision variable.
a	The market scale during COVID-19, $a>0$.	p	The adjusted price for one-unit object.
b_b	The PHC efforts coefficient to the demand from Player 3, $b_b>0$.	b_m	The PHC efforts coefficient to the demand from the upstream Players 1 and 2, $b_m>0$
e	The price coefficient to the demand, $e>0$	$f(\cdot)$	The probability density function for demand uncertainty ε .
$F(\cdot)$	The invertible distribution function for demand uncertainty ε .	$b_b\cdot i_b$	Healthy confidence of customers
μ	The mean of ε .	σ	The standard deviation of ε .
Notations for Parameters			
c_s	The unitary cost of Player 1.	c_m	The unitary cost of Player 2.
c_b	The unitary cost of Player 3. (directly related to objects)	X	The fixed cost of Player 3. (not directly related to objects)
w_s	The wholesale price of Player 1.	w_m	The wholesale price of Player 2.
h_s	The cost factor to PHC efforts of Player 1	h_m	The cost factor to PHC efforts of Player 2
h_b	The cost factor to PHC efforts of Player 3	H_s	The basic pandemic control costs of Player 1, like vaccines.
H_m	The basic pandemic control costs of Player 2, like vaccines.	H_b	The basic pandemic control costs of Player 3, like vaccines.
t	The time cost factor of Player 2	p_0	The original price for one-unit object before COVID-19.
s	The salvage price/leftover cost of spare objects.	v	The goodwill cost of one-unit unsatisfied

			demand
M	The budget of PHC subsidy provided by the government and communities	γ	The sharing ratio of the cost-sharing contract
ω	The adjusted wholesale price of the wholesale-price contract	ϑ	The sharing ratio of the revenue-sharing contract
α	The sharing ratio of the PHC costs for Player 3, $\alpha \in [0,1]$.	β	The sharing ratio of the PHC costs for Player 2, $\beta \in [0,1]$.
Notations for Decision Variables			
i_b	The PHC efforts of Player 3	i_m	The PHC efforts level of Player 2
i_s	The PHC efforts level of Player 1	p	The adjusted price for one-unit object.
q	The expected quantity of objects	r	The stocking factor, $r = q - y(i_b, i_m, i_s, p)$.
z	Player 2's decisions on whether to deliver goods. $z = \{0,1\}$.		

The strategic interaction among the exporter, logistic service provider, and importer is captured in Figure 3: Play 1 sets its public health efforts i_s based on Player 2's decision to deliver goods or not; Player 2 decides whether to deliver z based on its costs of public health efforts i_m upon receiving order quantity from Player 3, as well as the range of sharing ratios of the cost-sharing contract γ; Player 3 determines the order quantity q, the adjusted price p, and its public health efforts i_b considering price-sensitive and health-conscious customers under an uncertain market, as well as the range of sharing ratios of revenue-sharing contract ϑ. A budgetary subsidy program is issued to cover the PHC costs for all domestic businesses, including Players 2 and 3. The PHC subsidy from the domestic government primarily supports all domestic enterprises, including Players 2 and 3.

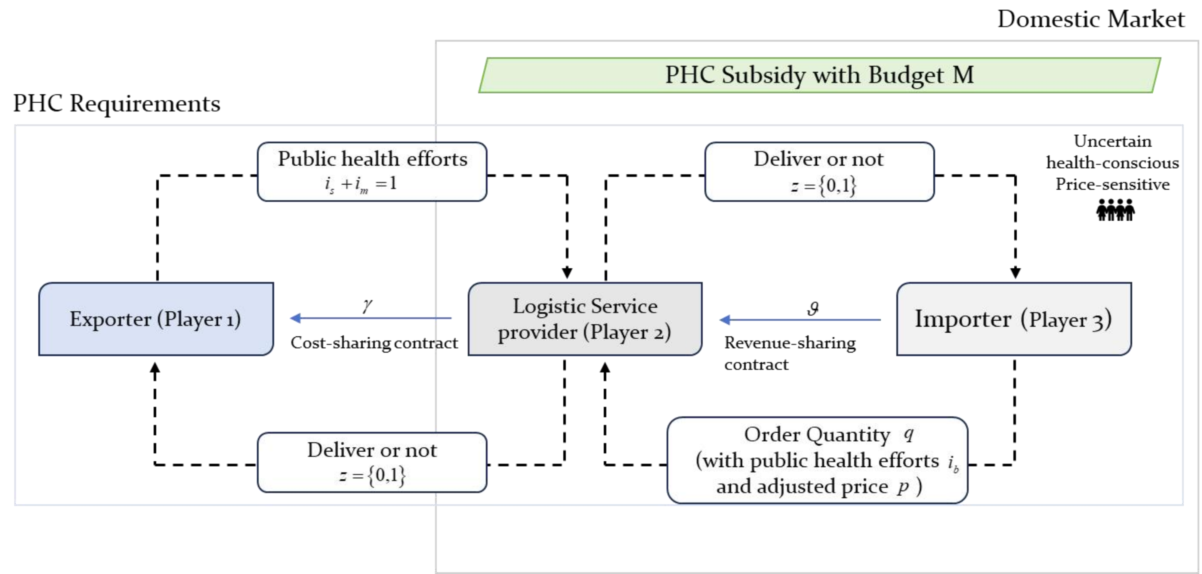

Figure 3. Strategic Interaction among stakeholders

The following assumptions are given to build the models:

Assumption 1: Exporting enterprises (Player 1) and logistics service providers (Player 2) should implement PHC measures, as $i_m + i_s = 1$. Logistics service providers may refuse to transport goods if PHC-related costs become prohibitively high to remain profitable, as $\mathrm{K} < \min\left[\left(w_m - w_s - c_m\right)q - \left(1-\beta\right)H_m,\ \left[\left(1-\beta\right)\cdot h_m + t\right]\cdot q\right]$.

Since $\left(w_m - w_s - c_m\right)q - \left(1-\beta\right)H_m$ is the threshold for Player 2 to achieve positive profitability. We assume a lower value of K to avoid a scenario where Player 2's profits remain at zero, as $K < \left(w_m - w_s - c_m\right)q - \left(1-\beta\right)H_m$. Additionally, K is less than the total PHC costs Player 2 would incur if solely responsible for all public health measures, as $i_m = 1$ with $K < \left[\left(1-\beta\right)\cdot h_m + t\right]\cdot q$.

Some countries have implemented strict import inspection and quarantine standards, which have complicated goods imports that raise costs to prevent indirect virus contact (Lu et al., 2021; Wang et al., 2021; WHO, 2012). Hence, we assume that Players 1 and 2 should put effort into PHC investment, including inspection and disinfection, etc. If the exporting enterprises cannot cover the necessary PHC costs of objects and packages, logistics services providers will refuse to transport any commodity out of high PHC costs and extra time costs required to achieve a healthy certificate, which is key to entering the importing country.

Assumption 2: The importer (Player 3) would put more PHC efforts into achieving higher healthy confidence $b_b \cdot i_b$ from customers, which is classified into 1-5 levels, $i_b \in \left[1,5\right]$.

SD levels of Player 3 are classified into Levels 1-5 based on its efforts on SD investment, as per the WHO (WHO, 2021). Level 1 refers to the minimum SD measures required by the government, mandated by the government, which are compulsory for normal business operations. Since no one has formulated the cost function of PHC efforts so far, we develop a quadratic cost function based on previous research works on investment costs by Li and Li (2016), Liu et al. (2012), Ghosh and Shah (2012), Xu et al. (2017), Basiri and Heydari (2017). Hence, the cost function of Player 3 is quadratic with increasing marginal cost, as $HC_b = h_b \cdot \left(i_b - 1\right)^2 + H_b$.

Assumption 3: The local demand is homogenous in its preference for health confidence and price adjustment, while the demand uncertainty follows a normal distribution.

Several businesses have adopted stricter public health measures beyond government mandates, as they have noticed that many customers now value these enhanced measures for reducing infection risks. Black Sheep restaurant, for instance, introduced a "COVID-19 playbook" to safeguard both guests and staff. Empirical research indicates that consumers are willing to pay more or wait longer for services with strong health protocols (Bosworth et al., 2015; Humphreys et al., 2023; Rossetti et al., 2022). Therefore, we assume that the demand function is price-sensitive and health-conscious. Huang, Leng, and Parlar (2013) comprehensively discussed the patterns of demand function used in previous research. Accordingly, we develop the demand function as $D(i_b, i_m, i_s, p, \varepsilon) = y(i_b, i_m, i_s, p) + \varepsilon$, $y(i_b, i_m, i_s, p) = a + b_b \cdot i_b + b_m \cdot (i_s + i_m) - ep$ based on works by Ray et al. (2005), Hu & Su (2018), Giri et al. (2021), etc. The random variable ε follows a normal distribution with probability density function $f(\cdot)$ and distribution function $F(\cdot)$. Demand cannot be negative, so that we assume that $\varepsilon \in [A, B]$, where $B = \inf$ and A is large enough to ensure positive demand for certain price ranges based on the works by Jiang and Wang (2010) and Hu and Su (2018). According to the work by Ray et al. (2005), we limit the range of adjusted prices within $p \in (c_b - p_0, p_0]$ to avoid unrealistic solutions. The lower bound $c_b - p_0$ means that the final price is larger than the production cost, as $p_0 + p > c_b$, while the upper bound p_0 limits the final price to no more than twice the original price. Hence, we set $A = ep_0 - a$ for the lower bound of the demand uncertainty for positive demand.

Assumption 4: The PHC subsidy budget benefits domestic enterprises by at least covering basic control costs. This subsidy prioritizes the construction of healthy supply chains, and thus Player 2 (domestic logistics service providers) gains subsidy priority.

According to works by Liu et al. (2021) and Tsao et al. (2021), the present research assumes that the PHC subsidy is subject to a fixed budget. This subsidy budget M covers $\alpha \cdot \left[h_b \cdot (i_b - 1)^2 + H_b\right] + \beta \cdot (h_m \cdot i_m \cdot q + H_m)$, and $M \geq \alpha H_b + \beta \cdot H_m$.

When $\alpha \cdot \left[h_b \cdot (i_b - 1)^2 + H_b\right] + \beta \cdot (h_m \cdot i_m \cdot q + H_m) < M$, all domestic businesses (Players 1 and 2) operate under the budget M; The condition of operating under budget M is equivalent to the scenario without a budget. When $\alpha \cdot \left[h_b \cdot (i_b - 1)^2 + H_b\right] + \beta \cdot (h_m \cdot i_m \cdot q + H_m) = M$, all domestic businesses operate just at the budget M; When $\alpha \cdot \left[h_b \cdot (i_b - 1)^2 + H_b\right] + \beta \cdot (h_m \cdot i_m \cdot q + H_m) > M$, all domestic businesses operate over the budget M. $M = 0$ indicates the extreme scenario where no subsidy is provided.

If $\alpha \cdot \left[h_b \cdot (i_b - 1)^2 + H_b\right] + \beta \cdot (h_m \cdot i_m \cdot q + H_m) > M$, the budget first subsidizes Player 2, and thus Player 3 obtains $M - \beta \cdot (h_m \cdot i_m \cdot q + H_m)$ of subsidy.

Assumption 5: Logistics service providers (Player 2) would bear higher PHC-related costs than exporting enterprises (Player 1), including higher PHC costs and extra time costs, if goods are delivered without COVID-19 negative labels, as $(1 - \beta) \cdot h_m + t > h_s$.

Player 2 incurs higher PHC costs and time costs because it has to unpack goods for COVID-19 testing, attach labels, and then repackage the goods if they lack COVID-19 negative labels, a process that can also be conducted by Player 1, as discussed in Figure 2.

Assumption 6: Apart from disruptions caused by COVID-19, no other unexpected events disrupt supply chain operations.

This research assumes an extreme scenario where the supply chain is completely disrupted by COVID-19 transmission. COVID-19 was characterized by its sporadic nature, with unpredictable outbreaks. Simultaneously, the pandemic persisted for an extended duration before being officially declared over. This combination of unpredictability and persistence created significant challenges for supply chain resilience. Therefore, no other unexpected events are considered, which simplifies the problem for the theoretical solution and focuses on PHC corridors.

3.2 Decentralized Supply Chain Model

3.2.1 Model Building for the decentralized model

Without cooperation, a supply chain is called decentralized where each player separately makes their own decisions for their individual optimality. It represents the basic level of the global supply chain PHC. Under this HSCC model, the importer serving customers (Player 3) decides its production and pricing strategy and PHC investment for customers' confidence in public health and makes orders based on market information. Its upstream player, the exporter like suppliers and manufacturers (Player 1) decides its PHC strategy upon the constraint from the logistics services provider (Player 2). Then, the logistics service provider (Player 2) determines their own PHC strategy and decides whether to transport goods accordingly. Players 1 and 2 should work together to attach COVID-19 negative labels on goods and packages and achieve a healthy certificate before entering importing borders. If Player 1 cannot cover the whole PHC costs along with production and packages, Player 2 would bear extra time costs as well as higher PHC costs out of unpacking and repackaging processes. The decentralized models are given below:

The profit function of the exporter (Player 1):

$$\pi_s(q,i_s) = (w_s - c_s)\cdot q - h_s \cdot i_s \cdot q \cdot z - H_s$$
$$s.t.\ \begin{cases} 0 \le i_s \le 1 \\ z = \begin{cases} 0, & \left[(1-\beta)\cdot(1-h_s)+t\right]\cdot i_m \cdot q > K \\ 1, & \left[(1-\beta)\cdot(1-h_s)+t\right]\cdot i_m \cdot q \le K \end{cases} \end{cases} \tag{1}$$

The profit function of the logistics services provider (Player 2):

$$\pi_m(q,i_m) = (w_m - w_s - c_m)\cdot q\cdot z - (1-\beta)\cdot(h_m\cdot i_m\cdot q\cdot z + H_m) - t\cdot i_m\cdot q\cdot z$$

$$s.t.\ \begin{cases} i_s + i_m = 1 \\ z = \begin{cases} 0, & \left[(1-\beta)\cdot h_m + t\right]\cdot i_m\cdot q > K \\ 1, & \left[(1-\beta)\cdot h_m + t\right]\cdot i_m\cdot q \le K \end{cases} \end{cases} \tag{2}$$

The profit function of the importer (Player 3):

$$\begin{aligned} \pi_b(q,p,i_b,i_m,i_s) = {} & (p_0 + p - c_b)\cdot \min\left[D, q\cdot z\right] - w_m\cdot q\cdot z + s\cdot\left[q\cdot z - D\right]^+ - v\cdot\left[D - q\cdot z\right]^+ \\ & -(1-\alpha)\cdot\left[h_b\cdot(i_b-1)^2 + H_b\right] - X \\ & -\left[\alpha\cdot\left[h_b\cdot(i_b-1)^2 + H_b\right] + \beta\cdot(h_m\cdot i_m\cdot q\cdot z + H_m) - M\right]^+ \end{aligned} \tag{3}$$

$$s.t.\ \ 1 \le i_b \le 5$$

3.2.2 Problem-Solving for the decentralized model

An importer-leader Stackelberg game is used to solve this problem. According to the Stackelberg steps, we first predict the decision behaviours of Player 1. From the first condition of the profit function of Player 1:

$$\frac{\partial \pi_s(q,i_s)}{\partial i_s} = -h_s\cdot q < 0 \tag{4}$$

It is monotonically decreasing with regard to i_s, we have the resulted $i_s = 0$ if we do not consider constraints from Player 2.

From the profit function of Player 2, the logistics services provider would reject to transport goods when $i_s^d = 0$. Considering the constraints $\left[(1-\beta)\cdot h_m + t\right]\cdot i_m\cdot q \le \mathrm{K}$ and $i_m + i_s = 1$, we have the best i_s as $i_s = 1 - \frac{\mathrm{K}}{\left[(1-\beta)\cdot h_m + t\right]q}$, and the best i_m as $i_m = \frac{\mathrm{K}}{\left[(1-\beta)\cdot h_m + t\right]q}$. Hence, we have the optimal Player 2's decision on delivery as $z = 1$.

A stocking factor $r = q - y(i_b, i_m, i_s, p)$ is adopted to achieve the best decision-making of the business based on the previous works by Thowsen (1975), Petruzzi and Dada (1999), Serel (2017), Wang and Diabat (2021), and Wang et al. (2024b). It is used to determine the optimal quantity for meeting uncertain demand. This riskless surplus can be compared with the demand uncertainty variable ε. When $r > \varepsilon$, product leftover occurs. Conversely, product shortage happens when $r < \varepsilon$.

Also, $\Lambda(r)=\int_A^r (r-x)f(x)dx$ is defined for the expected leftover and $\Gamma(r)=\int_r^B (x-r)f(x)dx$ for the expected shortage. With the results of $i_s = 1-\frac{\mathrm{K}}{\left[(1-\beta)\cdot h_m + t\right]q}$ and $i_m = \frac{\mathrm{K}}{\left[(1-\beta)\cdot h_m + t\right]q}$, the expected profit function of the business can be written as:

$$
\begin{aligned}
E\left[\pi_b(r,p,i_b)\right] = {} & (p_0+p-c_b-w_m)\cdot\left[y(i_s,p)+\mu\right]-(1-\alpha)\cdot\left[h_b\cdot(i_b-1)^2+H_b\right]-X \\
& -(w_m-s)\cdot\Lambda(r)-(p_0+p-c_b-w_m+v)\cdot\Gamma(r) \\
& -\left[\alpha\cdot\left[h_b\cdot(i_b-1)^2+H_b\right]+\beta\cdot\left(\frac{h_m\cdot\mathrm{K}}{(1-\beta)\cdot h_m+t}+H_m\right)-M\right]^+ \\
s.t. \quad & 1\le i_b\le 5
\end{aligned} \tag{5}
$$

The expressions of $(p_0+p-c_b-w_m)\cdot\left[y(i_s,p)+\mu\right]-(1-\alpha)\cdot\left[h_b\cdot(i_b-1)^2+H_b\right]-X$ and $(p_0+p-c_b-w)\cdot\left[y(i_s,p)+\mu\right]-h_b\cdot(i_b-1)^2-H_b+M-\beta\cdot\left(\frac{h_m\cdot\mathrm{K}}{(1-\beta)\cdot h_m+t}+H_m\right)-X$ refer to the riskless profitability for under or over the Budget M, respectively. $(w_m-s)\cdot\Lambda(r)+(p_0+p-c_b-w_m+v)\cdot\Gamma(r)$ refers to the uncertainty cost, where $(w_m-s)\cdot\Lambda(r)$ is the leftover costs and $(p_0+p-c_b-w_m+v)\cdot\Gamma(r)$ is the shortage costs.

From *Proof 1* in the Appendix, we can achieve the optimal results by using the Lagrange process, as shown below:

Table 2. Results of the Decentralized Model

Results under Budget M

$$
\begin{cases}
z^{D_1*}=1 \\
i_s^{D_1*}=1-\dfrac{\mathrm{K}}{\left[(1-\beta)\cdot h_m+t\right]q^{D_1*}} \\
i_m^{D_1*}=\dfrac{\mathrm{K}}{\left[(1-\beta)\cdot h_m+t\right]q^{D_1*}} \\
i_b^{D_1*}=\dfrac{2e\cdot\theta_1\left(r^{D_1*}\right)-a-b_m-\mu+e\left(p_0-c_b-w_m\right)+\Gamma\left(r^{D_1*}\right)}{b_b} \\
p^{D_1*}=\dfrac{a+b_b\cdot i_b^{D_1*}+b_m+\mu-e\left(p_0-c_b-w_m\right)-\Gamma\left(r^{D_1*}\right)}{2e} \\
q^{D_1*}=a+b_b\cdot i_b^{D_1*}+b_m-e\cdot p^{D_1*}+r^{D_1*} \\
r^{D_1*}\ by\ solving\ \Theta_1(r) \\
\Theta_1(r):F(r)=\dfrac{p_0+\theta_1(r)+v-w_m-c_b}{p_0+\theta_1(r)+v-s-c_b} \\
\theta_1(r)=\dfrac{b_b^2\cdot\left(p_0-c_b-w_m\right)+2(1-\alpha)\cdot h_b\cdot\left[a+b_b+b_m+\mu-e\cdot\left(p_0-c_b-w_m\right)-\Gamma(r)\right]}{4(1-\alpha)\cdot h_b\cdot e-b_b^2}
\end{cases}
$$

Results at Budget M

$$
\begin{cases}
z^{D_2*}=1 \\
i_s^{D_2*}=1-\dfrac{\mathrm{K}}{\left[(1-\beta)\cdot h_m+t\right]q^{D_2*}} \\
i_m^{D_2*}=\dfrac{\mathrm{K}}{\left[(1-\beta)\cdot h_m+t\right]q^{D_2*}} \\
i_b^{D_2*}=1+\sqrt{\dfrac{M-\beta\cdot\left(\dfrac{h_m\cdot\mathrm{K}}{(1-\beta)\cdot h_m+t}+H_m\right)-\alpha\cdot H_b}{\alpha\cdot h_b}} \\
p^{D_2*}=\theta_2\left(r^{d_2*}\right) \\
q^{D_2*}=a+b_b\cdot i_b^{d_2*}+b_m-e\cdot p^{d_2*}+r^{d_2*} \\
r^{D_2*}\ by\ solving\ \Theta_2(r) \\
\Theta_2(r):\theta_2(r)\left[1-F(r)\right]=w_m-s \\
\theta_2(r)=\dfrac{a+b_b\cdot i_b^{d_2*}+b_m+\mu-e\left(p_0-c_b-w_m\right)-\Gamma(r)}{2e}
\end{cases}
$$

Results over Budget M

$$
\begin{cases}
z^{D_3*} = 1 \\
i_s^{D_3*} = 1 - \dfrac{\mathrm{K}}{\left[(1-\beta)\cdot h_m + t\right] q^{D_3*}} \\
i_m^{D_3*} = \dfrac{\mathrm{K}}{\left[(1-\beta)\cdot h_m + t\right] q^{D_3*}} \\
i_b^{D_3*} = \dfrac{2e\cdot\theta_3\left(r^{D_3*}\right) - a - b_m - \mu + e\cdot(p_0 - c_b - w) + \Gamma\left(r^{D_3*}\right)}{b_b} \\
p^{D_3*} = \dfrac{a + b_b\cdot i_b^{D_3*} + b_m + \mu - e\cdot(p_0 - c_b - w) - \Gamma\left(r^{D_3*}\right)}{2e} \\
q^{D_3*} = a + b_b\cdot i_b^{D_3*} + b_m - e\cdot p^{D_3*} + r^{D_3*} \\
r^{D_3*} \text{ by solving } \Theta_3(r) \\
\Theta_3(r): F(r) = \dfrac{p_0 + \theta_3(r) + v - w - c_b}{p_0 + \theta_3(r) + v - s - c_b} \\
\theta_3(r) = \dfrac{b_b^2\cdot(p_0 - c_b - w) + 2h_b\cdot\left[a + b_b + b_m + \mu - e\cdot(p_0 - c_b - w) - \Gamma(r)\right]}{4h_b\cdot e - b_b^2}
\end{cases}
$$

According to Table 2, the optimal decentralized strategy $\left(i_s^{D*}, i_m^{D*}, i_b^{D*}, p^{D*}, r^{D*}\right)$ can be determined by comparing profits obtained under, at, or over the Budget M. Thus, we have the optimal profits for the entire supply chain π^{D*}, Player 1 π_s^{D*}, Player 2 π_m^{D*}, and Player 3 π_b^{D*} in the decentralized model.

3.3 Integrated Supply Chain Model

3.3.1 Model Building for the integrated model

Ideally, the supply chain is integrated with full centralization, where a central decision-maker has the authority to make decisions for all supply chain insiders to achieve overall optimality. This pattern is rare but exists in some industries or sectors, like the vendor-managed inventory (VMI) program (Duan & Liao, 2013) and some motor industry (Wang & Choi, 2020c). The integrated decision-making approach reduces the negative effects of unpredictable dynamics, like bullwhip effects (Giannoccaro, 2018). Moreover, maximum profitability can be achieved with improved efficiency. This model acts as an idealized benchmark model. The profit function of the integrated model is shown below:

$$
\begin{aligned}
&\pi\left(q,p,i_b,i_m,i_s\right)\\
&=\left(p_0+p-c_b\right)\cdot\min\left[D,q\cdot z\right]-\left(c_s+c_m\right)\cdot q\cdot z+s\cdot\left[q\cdot z-D\right]^{+}-v\cdot\left[D-q\cdot z\right]^{+}\\
&\ -\left(1-\alpha\right)\cdot\left[h_b\cdot\left(i_b-1\right)^2+H_b\right]-\left(1-\beta\right)\cdot\left(h_m\cdot i_m\cdot q\cdot z+H_m\right)\\
&\ -\left[\alpha\cdot\left[h_b\cdot\left(i_b-1\right)^2+H_b\right]+\beta\cdot\left(h_m\cdot i_m\cdot q\cdot z+H_m\right)-M\right]^{+}\\
&-t\cdot i_m\cdot q\cdot z-h_s\cdot i_s\cdot q\cdot z-H_s-X\\
&s.t.\ \ 1\le i_b\le 5;\ i_m+i_s=1
\end{aligned}
\tag{6}
$$

3.3.2 Problem-Solving for the integrated model

As the PHC measures before delivery are necessary, the integrated model first decides who bears the investment costs. As mentioned in Assumption 5, $\left(1-\beta\right)\cdot h_m+t>h_s$ and $h_m+t>h_s$, the exporter (Player 1) decides $i_s=1$. Hence, we have $z=1$ to deliver goods from exporter to importer.

From *Proof 2* in the Appendix, we can achieve the optimal results, as shown below:

Table 3. Results of the Integrated Model

Results under Budget M
$\begin{cases} z^{I_1*}=1;\ i_s^{I_1*}=1;\ i_m^{I_1*}=0\\ i_b^{I_1*}=\dfrac{2e\cdot\varphi_1\left(r^{I_1*}\right)-a-b_m-\mu+e\cdot\left(p_0-c_s-c_m-c_b-h_s\right)+\Gamma\left(r^{I_1*}\right)}{b_b}\\ p^{I_1*}=\dfrac{a+b_b\cdot i_b^{I_1*}+b_m+\mu-e\cdot\left(p_0-c_s-c_m-c_b-h_s\right)-\Gamma\left(r^{I_1*}\right)}{2e}\\ q^{I_1*}=a+b_b\cdot i_b^{I_1*}+b_m-e\cdot p^{I_1*}+r^{I_1*}\\ r^{I_1*}\ by\ solving\ \mathrm{T}_1\left(r\right)\\ T_1\left(r\right):F\left(r\right)=\dfrac{p_0+\varphi_1\left(r\right)+v-c_s-c_m-c_b-h_s}{p_0+\varphi_1\left(r\right)+v-s-c_b}\\ \varphi_1\left(r\right)=\dfrac{b_b^2\cdot\left(p_0-c_s-c_m-c_b-h_s\right)+2\left(1-\alpha\right)\cdot h_b\cdot\left[a+b_b+b_m+\mu-e\cdot\left(p_0-c_s-c_m-c_b-h_s\right)-\Gamma\left(r\right)\right]}{4\left(1-\alpha\right)\cdot h_b\cdot e-b_b^2} \end{cases}$
Results at Budget M

$$\begin{cases} z^{I_2*}=1;\ i_s^{I_2*}=1;\ i_m^{I_2*}=0 \\ i_b^{I_2*}=1+\sqrt{\dfrac{M-\beta\cdot H_m-\alpha H_b}{\alpha h_b}} \\ p^{I_2*}=\dfrac{a+b_b\cdot i_b^{I_2*}+b_m+\mu-e\left(p_0-c_s-c_m-c_b-h_s\right)-\Gamma\left(r^{I_2*}\right)}{2e} \\ q^{I_2*}=a+b_b\cdot i_b^{I_2*}+b_m-e\cdot p^{I_2*}+r^{I_2*} \\ r^{I_2*}\ by\ solving\ \Theta_2(r) \\ \mathrm{T}_2(r):F(r)=\dfrac{p_0+\varphi_2(r)+v-c_s-c_m-c_b-h_s}{p_0+\varphi_2(r)+v-s-c_b} \\ \varphi_2(r)=\dfrac{a+b_b\cdot\left(1+\sqrt{\dfrac{M-\beta\cdot H_m-\alpha H_b}{\alpha h_b}}\right)+b_m+\mu-e\cdot\left(p_0-c_s-c_m-c_b-h_s\right)-\Gamma(r)}{2e} \end{cases}$$

Results over Budget M

$$\begin{cases} z^{I_3*}=1;\ i_s^{I_3*}=1;\ i_m^{I_3*}=0 \\ i_b^{I_3*}=\dfrac{2e\cdot\varphi_3\left(r^{I_3*}\right)-a-b_m-\mu+e\cdot\left(p_0-c_s-c_m-c_b-h_s\right)+\Gamma\left(r^{I_3*}\right)}{b_b} \\ p^{I_3*}=\dfrac{a+b_b\cdot i_b^{I_3*}+b_m+\mu-e\cdot\left(p_0-c_s-c_m-c_b-h_s\right)-\Gamma\left(r^{I_3*}\right)}{2e} \\ q^{I_3*}=a+b_b\cdot i_b^{I_3*}+b_m-e\cdot p^{I_3*}+r^{I_3*} \\ r^{I_3*}\ by\ solving\ \mathrm{T}_3(r) \\ \mathrm{T}_3(r):F(r)=\dfrac{p_0+\varphi_3(r)+v-c_s-c_m-c_b-h_s}{p_0+\varphi_3(r)+v-s-c_b} \\ \varphi_3(r)=\dfrac{b_b^2\cdot\left(p_0-c_s-c_m-c_b-h_s\right)+2h_b\cdot\left[a+b_b+b_m+\mu-e\left(p_0-c_s-c_m-c_b-h_s\right)-\Gamma(r)\right]}{4h_b\cdot e-b_b^2} \end{cases}$$

According to Table 3, the optimal integrated strategy $\left(i_s^{I*}, i_m^{I*}, i_b^{I*}, p^{I*}, r^{I*}\right)$ can be determined by comparing profits obtained under, at, or over the Budget M. Thus, we have the optimal profits for the entire supply chain π^{I*}, Player 1 π_s^{I*}, Player 2 π_m^{I*}, and Player 3 π_b^{I*} in the integrated model.

3.4 Coordinated Supply Chain Model

3.4.1 Model Building for the coordinated model

As decentralized decision-making inevitably causes profit discrepancy, the PHC supply chain members attempt to conduct coordination achievable through contracts for higher profitability, even the integrated performance. This model sets forth the advanced level of the global supply chain PHC with coordination strategies. Correspondingly, a cost-sharing contract is used to coordinate the exporter (Player 1) and logistics services provider (Player 2), while collaboration between the importer (Player 3) and logistics services provider (Player 2) is achieved through a joint revenue-sharing and wholesale price contract. With well-designed contracts, Player 1 will conduct PHC measures for healthy labels, while Player 2 promises to cover parts of the corresponding PHC costs. Player 3 enjoys the benefits of PHC implementation, and thus it promises to share some revenue with Player 2, who also adjusts its wholesale price for high overall performance. The coordinated models are developed as follows:

The profit function of the exporter (Player 1):

$$\pi_s(q,i_s) = (w_s - c_s)\cdot q\cdot z - (1-\gamma)i_s \cdot h_s \cdot q \cdot z - H_s$$

$$s.t.\begin{cases} 0 \le i_s \le 1 \\ \gamma \begin{cases} = 0, \text{ if } i_s < 1 \\ > 0, \text{ if } i_s = 1 \end{cases} \\ z = \begin{cases} 0, & \left[(1-\beta)\cdot(1-h_s)+t\right]\cdot i_m \cdot q > K \\ 1, & \left[(1-\beta)\cdot(1-h_s)+t\right]\cdot i_m \cdot q \le K \end{cases} \end{cases} \tag{7}$$

The profit function of the logistics service provider (Player 2):

$$\pi_m(q,i_m) = (w_m + \omega - w_s - c_m)\cdot q\cdot z - (1-\beta)\cdot H_m - \gamma\cdot h_s \cdot q\cdot z + \vartheta\cdot R(q,p,i_b) - t\cdot i_m \cdot q\cdot z$$

$$s.t.\begin{cases} i_s + i_m = 1 \\ z = \begin{cases} 0, & \left[(1-\beta)\cdot h_m + t\right]\cdot i_m \cdot q > K \\ 1, & \left[(1-\beta)\cdot h_m + t\right]\cdot i_m \cdot q \le K \end{cases} \end{cases} \tag{8}$$

The profit function of the importer (Player 3):

$$\begin{aligned} &\pi_b(q,p,i_b) = (1-\vartheta)\cdot R(q,p,i_b) - X \\ &R(q,p,i_b) = (p_0 + p - c_b)\cdot \min[D, q\cdot z] - (w_m + \omega)\cdot q\cdot z + s\cdot[q\cdot z - D]^+ - v\cdot[D\cdot z - q]^+ \\ &\qquad - (1-\alpha)\cdot\left[h_b\cdot(i_b-1)^2 + H_b\right] - \left[\alpha\cdot\left[h_b\cdot(i_b-1)^2 + H_b\right] + \beta\cdot H_m - M\right]^+ \\ &s.t.\;\; 1 \le i_b \le 5 \end{aligned} \tag{9}$$

3.4.2 Problem-Solving for the coordinated model

An importer-leader Stackelberg game is used to solve this problem. According to the Stackelberg steps, we first predict the decision behaviours of Player 1. From the first condition of the profit function of Player 1:

$$\frac{\partial \pi_s(q,i_s)}{\partial i_s} = -(1-\gamma)h_s \cdot q < 0 \tag{10}$$

It is monotonically decreasing with regard to i_s, we have the resulted $i_s = 0$ and $\gamma = 0$ if we do not consider constraints of Players 1 and 2. Considering constraints $\gamma = 0, \text{ if } i_s < 1$ and $z = \begin{cases} 0, & \left[(1-\beta)\cdot h_m + t\right]\cdot i_m \cdot q > K \\ 1, & \left[(1-\beta)\cdot h_m + t\right]\cdot i_m \cdot q \le K \end{cases}$, we have $\begin{cases} i_s = 1 - \dfrac{K}{\left[(1-\beta)\cdot h_m + t\right]q} \\ \gamma = 0 \end{cases}$ or $\begin{cases} i_s = 1 \\ \gamma > 0 \end{cases}$. When $(1-\gamma)h_s \cdot q < h_s \cdot i_s \cdot q$ is constantly achieved, the best solution is $\begin{cases} i_s = 1 \\ \gamma > 0 \end{cases}$. Hence, we have the boundary of γ as $\gamma > \dfrac{K}{\left[(1-\beta)\cdot h_m + t\right]q}$. From $i_s + i_m = 1$, we have $i_m = 0$. This problem can be solved by the Stackelberg process with Lagrange optimization, as shown in *Proof 3* in the Appendix. The optimal results are achieved below:

Table 4. Results of Coordinated Model

Results under Budget M
$\begin{cases} z^{C_1*} = 1;\ i_s^{C_1*} = 1;\ i_m^{C_1*} = 0 \\ i_b^{C_1*} = \dfrac{2\cdot ep^{C_1*} - a - b_m - \mu + e\cdot(p_0 - c_b - w_m - \omega) + \Gamma\left(r^{C_1*}\right)}{b_b} \\ p^{C_1*} = \dfrac{a + b_b\cdot i_b^{C_1*} + b_m + \mu - e\cdot(p_0 - c_b - w_m - \omega) - \Gamma\left(r^{C_1*}\right)}{2e} \\ q^{C_1*} = a + b_b\cdot i_b^{C_1*} + b_m - e\cdot p^{C_1*} + r^{C_1*} \\ r^{C_1*} \text{ by solving } \Omega_1(r) \\ \Omega_1(r): F(r) = \dfrac{p_0 + \upsilon_1(r) + v - w_m - \omega - c_b}{p_0 + \upsilon_1(r) + v - s - c_b} \\ \upsilon_1(r) = \dfrac{b_b^2(p_0 - c_b - w_m - \omega) + 2\cdot(1-\alpha)\cdot h_b\cdot\left[a + b_b + b_m + \mu - e\cdot(p_0 - c_b - w_m - \omega) - \Gamma(r)\right]}{4\cdot(1-\alpha)\cdot h_b\cdot e - b_b^2} \end{cases}$
Results at Budget M
$\begin{cases} z^{C_2*} = 1;\ i_s^{C_2*} = 1;\ i_m^{C_2*} = 0 \\ i_b^{C_2*} = 1 + \sqrt{\dfrac{M - \beta\cdot H_m - \alpha H_b}{\alpha h_b}} \\ p^{C_2*} = \dfrac{a + b_b\cdot i_b^{C_2*} + b_m + \mu - e\cdot(p_0 - c_b - w_m - \omega) - \Gamma\left(r^{C_2*}\right)}{2e} \\ q^{C_2*} = a + b_b\cdot i_b^{C_2*} + b_m - e\cdot p^{C_2*} + r^{C_2*} \\ r^{C_2*} \text{ by solving } \Omega_2(r) \\ \Omega_2(r): F(r) = \dfrac{p_0 + \upsilon_2(r) + v - w_m - \omega - c_b}{p_0 + \upsilon_2(r) + v - s - c_b} \\ \upsilon_2(r) = \dfrac{a + b_b\cdot\left(1 + \sqrt{\dfrac{M - \beta\cdot H_m - \alpha H_b}{\alpha h_b}}\right) + b_m + \mu - e\cdot(p_0 - c_b - w_m - \omega) - \Gamma(r)}{2e} \end{cases}$

Results over Budget M
$\begin{cases} z^{C_3*}=1;\ i_s^{C_3*}=1;\ i_m^{C_3*}=0 \\ i_b^{C_3*}=\dfrac{2\cdot ep^{C_3*}-a-b_m-\mu+e\cdot(p_0-c_b-w_m-\omega)+\Gamma\left(r^{C_3*}\right)}{b_b} \\ p^{C_3*}=\dfrac{a+b_b\cdot i_b^{C_3*}+b_m+\mu-e\cdot(p_0-c_b-w_m-\omega)-\Gamma\left(r^{C_3*}\right)}{2\cdot e} \\ q^{C_3*}=a+b_b\cdot i_b^{C_3*}+b_m-e\cdot p^{C_3*}+r^{C3*} \\ r^{C_3*}\ by\ solving\ \Omega_3(r) \\ \Omega_3(r):F(r)=\dfrac{p_0+\upsilon_3(r)+v-w_m-\omega-c_b}{p_0+\upsilon_3(r)+v-s-c_b} \\ \upsilon_3(r)=\dfrac{b_b^2\cdot(p_0-c_b-w_m-\omega)+2h_b\cdot\left[a+b_b+b_m+\mu-e\cdot(p_0-c_b-w_m-\omega)-\Gamma(r)\right]}{4\cdot h_b\cdot e-b_b^2} \end{cases}$

According to Table 4, the optimal decentralized strategy $\left(i_s^{C*},i_m^{C*},i_b^{C*},p^{C*},r^{C*}\right)$ can be determined by comparing profits obtained under, at, or over the Budget M. Thus, we have the optimal profits for the entire supply chain π^{C*}, Player 1 π_s^{C*}, Player 2 π_m^{C*}, and Player 3 π_b^{C*} in the coordinated model.

3.5 Discussion

The coordinated model aims to drive the PHC supply chain profitability up to the integrated level through the contract settings. From *Proof 4* in the Appendix, if the adjusted wholesale price satisfies $\omega+w_m=c_s+c_m+h_s$, the profits of the coordinated supply chain will achieve the integrated level. This means the PHC can achieve full coordination through the joint revenue-sharing and wholesale-price contract, while the revenue-sharing and cost-sharing ratios decide the profit distribution among supply chain players. Otherwise, the supply chain achieves partial coordination, under which the supply chain profitability becomes better than the decentralized one, but does not reach the integrated level.

Proposition 1: Full coordination is achievable through joint revenue-sharing and wholesale-price contracts if the contract settings meet the relationship of $\omega+w_m=c_s+c_m+h_s$, otherwise the supply chain benefits from partial cooperation but cannot achieve maximum profit.

Given $\omega+w_m=c_s+c_m+h_s$, the optimal profits of both the whole PHC and its insiders are given as:

$$\begin{cases} \pi_s^{C*}(q,i_s)=\left[w_s-c_s-(1-\gamma)\cdot h_s\right]\cdot q^{I*}-H_s \\ \pi_m^{C*}(q,i_m)=(c_s+h_s-w_s)\cdot q^{I*}-(1-\beta)\cdot H_m-\gamma\cdot h_s\cdot q^{I*}+\vartheta\cdot\left[\pi^{I*}+F+H_s+(1-\beta)\cdot H_m\right] \\ \pi_b^{C*}(q,p,i_b)=(1-\vartheta)\cdot\left[\pi^{I*}+H_s+(1-\beta)\cdot H_m\right]-\vartheta\cdot X \\ \pi^{C*}=\pi^{I*} \end{cases} \quad (11)$$

Since coordination surges the overall profitability, Pareto improvement discusses if all the players benefit from these contracts or at least one becomes better off without anyone's loss. It is key to perform contracts in practice. This requires $\pi_s^{C*}(q,i_s) \geq \pi_s^{D*}(q,i_s)$, $\pi_m^{C*}(q,i_m) \geq \pi_m^{D*}(q,i_m)$ and $\pi_b^{C*}(q,p,i_b) \geq \pi_b^{D*}(q,p,i_b)$, which is determined by the cost-sharing ratio of γ and revenue sharing ratio of ϑ. From the above problem-solving process, we have the lower boundary of γ as $\gamma > \frac{K}{[(1-\beta)\cdot h_m + t]q}$. From the Pareto improvement conditions of Player 2, $[(1-\beta)\cdot h_m + t]\cdot i_m > \gamma h_s$ and $\pi_m^{C*} > \pi_m^{D*}$, we have $\gamma < \frac{K}{h_s q}$ and $\gamma < \chi$, where χ is obtained by solving $\pi_m^{C*} > \pi_m^{D*}$. Hence, we have the upper boundary of γ as $\gamma < \min\left[\frac{K}{h_s q}, \chi, 1\right]$. Additionally, the boundaries of ϑ can be obtained by solving $\pi_m^{C*} > \pi_m^{D*}$ and $\pi_b^{C*} > \pi_b^{D*}$. We have $\nu < \vartheta < \tau$, where ν and τ are obtained by solving $\pi_m^{C*} > \pi_m^{D*}$ and $\pi_b^{C*} > \pi_b^{D*}$, respectively. It is hard to analytically express the Pareto-efficient conditions out of the complicated results, however, we can achieve the boundaries of γ and ϑ for Pareto-improvement if the datasets are well-prepared. This research will conduct an in-depth discussion in the following Numerical Analysis section.

Proposition 2: Given the contract settings of full coordination, Pareto improvement is determined by the cost-sharing ratio of γ and revenue sharing ratio of ϑ. When $\frac{K}{[(1-\beta)\cdot h_m + t]q} < \gamma < \min\left[\frac{K}{h_s q}, \chi, 1\right]$, exporting-related enterprises (Players 1 and 2) are more likely to engage in cost-sharing contracts. When $\nu < \vartheta < \tau$, importing-related enterprises (Players 2 and 3) are more likely to engage in revenue-sharing contracts. Contract-makers should deliberate them to make contracts into fruition when datasets are settled.

From *Proof 5* in the Appendix, we have $i_b^{D*} < i_b^{C*} \leq i_b^{I*}$ and $q^{D*} < q^{C*} \leq q^{I*}$, which imply that PHC coordination contributes to a safer environment and better customer maintenance. $p^{I*} \leq p^{C*} < p^{D*}$ indicates that the importer (Player 3) could stay competitive on price, and the end customers can enjoy a better price under a safer environment. As $\pi^{D*} < \pi^{C*} \leq \pi^{I*}$, the PHC coordination drives up the profitability of the whole chain. When $\omega + w_m = c_s + c_m + h_s$ is satisfied for full coordination, the results of the coordinated model are equal to those of the integrated model.

Proposition 3: A healthier environment is achievable through PHC coordination as well as an increase in profitability.

Since PHC measures impose extra costs on supply chains, its players would transfer their financial pressure to their downstream customers through raising prices. Since $p^{I*} \le p^{C*} < p^{D*}$ and $q^{D*} < q^{C*} \le q^{I*}$, the coordinated PHC raise prices less than the decentralized one with more order quantity. Thus, PHC players stay competitive on price and customer maintenance through coordination.

Proposition 4: PHC players stay competitive on price and customer maintenance through coordination.

Since $p^{I*} \le p^{C*} < p^{D*}$ and $i_b^{D*} < i_b^{C*} \le i_b^{I*}$, the price of goods in a coordinated PHC is smaller than that of a decentralized one. Moreover, the coordinated PHC performs better in PHC measures. Hence, customers in coordinated PHC can enjoy a better price in a healthier environment with higher PHC efforts.

Proposition 5: Customers can enjoy a better price under a safer environment through PHC coordination, which relieves the financial pressures and mental stress of the general public, especially vulnerable people suffering from the lasting COVID-19 pandemic.

IV. ANALYSIS AND RESULTS

The proposed HSCC model is suitable for global supply chain PHC with COVID-19-prone objects. It can also theoretically analyse the emerging "Travel Bubbles" by regarding tourists as COVID-19-susceptible objects in tourism supply chains. The global cold chain is reportedly a major source of cross-border COVID-19 cases and hence bears many social responsibilities and legal obligations in controlling pandemic transmissions for public health. Therefore, the data collected from global cold chains, as shown in Table 5, are used in this numerical study.

Table 5. Data Values

w_s	w_m	p_0	c_s	c_m	c_b	h_s	h_m
30	60	100	15	10	10	5	8
USD	USD	USD	USD	USD	USD	USD	USD
h_b	v	s	t	K	X	H_s	H_m
500	10	10	10	1800	5000	500	500
100USD	USD	USD	USD	100USD	100USD	100USD	100USD
H_b	M	ω	α	β	γ	ϑ	
500	1000	-30	0.5	0.4	0.6	0.35	
100USD	100USD	USD	--	--	--	--	

The market information is collected from a seafood market with the original market scale of 250 (unit: 100) before COVID-19 outbreaks. Accordingly, we assume that the COVID-19-bearing demand function is built as $y(i_b, i_m, i_s, p) = 180 + 10i_b + 5(i_m + i_s) - 3p + \varepsilon$ (unit:100) with $\mu = 20$ and $\sigma = 20$.

4.1 Numerical Results

Given the dataset above, the performances and behaviours of the whole PHC and its members are numerically addressed in Table 6. The first three rows show that the logistics service provider (Player 2) will conduct PHC measures with considerable time costs in the decentralized model, while the PHC measures would be implemented by the exporter (Player 1), and Player 2 bears the corresponding PHC costs but saves time costs in the coordinated PHC model. Although the PHC costs of Player 2 increase by around 9.28%, its time costs sharply decrease. Hence, the total PHC-related costs substantially decrease by nearly 22.13% through coordination. Moreover, the importer (Player 3) would like to invest more in social distancing measures, from 2.0284 to 2.3541, for a healthier environment, which increases customers' confidence in public health. In turn, customers are more willing to consume in a safer market.

The implementation of PHC will reopen the borders among regions and countries with smooth and healthy supply chain operations. The decentralized PHC requires the exporting-related stakeholders (Players 1 and 2) to conduct control measures to reopen the borders and transport goods, while the coordinated PHC is proposed for better supply chain operations. It achieves 163.597 quantity in the decentralized model and 221.4994 quantity in the coordinated one. Compared with the original market scale of 250 before COVID-19, the decentralized PHC resumes the global supply chain operations to some extent, while the coordinated PHC has the potential to bring the operations closer to the near-normal.

The coordinated PHC can achieve integrated profitability through contract-based coordination, which is much larger than that of the decentralized PHC. Pareto improvement is achieved as the profits of all the players increase after coordination, and thus they all have incentives to join in the G3P partnerships for healthy supply chain operations. Also, PHC will raise selling prices due to the extra PHC-related costs, including the PHC costs and time costs. It is obvious that implementing PHC measures largely increases the selling price in the decentralized model. However, the coordinated PHC can increase the price much less than the decentralized one (7.7069 vs. 21.4213), but enjoys a larger customer quantity, from 163.60 to 221.50. Hence, customers enjoy a better price through coordination, and are more willing to make a purchase; local businesses stay competitive in price and customer maintenance. Coordination eliminates time costs, as all public health measures are handled by Player 1, as illustrated in Figure 2 and Table 4. Player 2 is exempt from PHC measures, which avoids any associated time costs, as is the integrated supply chain. Furthermore, the coordinated PHC consumes less subsidy than the decentralized PHC. The subsidy required is 1103.61 in the decentralized PHC, over the budget of 1000, while it drops to 908.42 in the coordinated PHC.

Therefore, the government and communities can spend the saved money in ways to better recover normal life through contract-based coordination.

Table 6. Numerical Results of the HSCC model

	Unit	Decentralized Model			Integrated Model	Coordinated Model		
		Player 1	Player 2	Player 3		Player 1	Player 2	Player 3
PHC effort level	--	0.2566	0.7434	2.0284	2.3541	1	0	2.3541
Time costs	USD	--	1216.22	--	0	--	0	--
PHC investment cost (uncovered by M)	100USD	709.88	883.78	552.34	2618.02	943.84	965.76	708.42
Subsidy	100USD	--	589.19	514.42	908.42	--	200	708.42
			1000				908.42	
Wholesale price	USD	30	60	--	--	30	30	--
Adjusted selling price	USD	--		21.4213	7.7069	--		7.7069
Stocking factor	100	22.58			36.50	36.50		
Expected quantity	100	163.60			221.50	221.50		
Profits	100USD	1744.08	1171.94	1780.19	6845.25	2384.96	1240.87	3219.41
Overall Profits	100USD	4696.21			6845.25	6845.24		

Based on the numerical results above, we conclude the following finding:

Findings 1: The decentralized PHC resumes the global supply chain operations to some extent, while PHC coordination contributes to near-normal orders, higher profitability, a healthier environment, larger purchasing power, and a better life for the general public. Thus, it is worthwhile to be practically implemented to create new norms. All the PHC stakeholders benefit from Pareto-efficient PHC coordination. The PHC costs less subsidy through contract-based G3P, and thus the government and communities can spend the saved money in ways that better recover people's lives to normal.

4.2 Sensitivity Analyses

This section identifies the dominating factors and then explores their impacts on the performances of the proposed HSCC model. It validates the utility and efficiency of the proposed HSCC model for the practical launch of the global supply chain PHC. The potential partnerships among PHC stakeholders are discussed with consideration of different supply chains and contract settings. Game equilibrium and boundaries are explored for optimality with Pareto improvement.

4.2.1 Sensitivity Analyses to market settings

This section highlights the profitability and KPIs of three PHC models under different markets, considering different demand uncertainties and healthy inclinations. Player 1 refers to the exporter; Player 2 refers to the logistics service provider; Player 3 refers to the importer.

Figures 4 and 5 indicate the trends of profitability and KPIs of three PHC models with various demand uncertainties, respectively. From Figure 4, the whole profits of all three models decrease with increasing demand uncertainties. However, the coordinated PHC always earns higher profitability.

Full coordination can be achieved through properly designed contracts. The profits of Players 2 and 3 drop with bigger demand fluctuation, while Player 1 enjoys a slight increase in profitability due to the increasing order quantity, see Figure 5. Pareto improvement is achievable through contracts when the demand uncertainty is under 1.5, after which Player 2 will earn less than the decentralized one. This means that the coordinated PHC has to adjust the contract settings, including cost-sharing and revenue-sharing ratios, for Pareto improvement if the demand uncertainty is larger than 1.5. From Figure 5, PHC can achieve better KPIs through coordination, including higher quantity, a smaller adjusted price, greater PHC efforts, and less subsidy used, like the previous conclusion from numerical results. Businesses under a higher demand uncertainty will hold a larger safety stock, which leads to greater risk costs. Thus, the adjusted selling prices slightly decrease to attract more price-sensitive customers to hedge costs of demand risks, and so does the PHC investment. Demand uncertainty has little influence on subsidy used, which experiences a small decrease with increasing uncertainties.

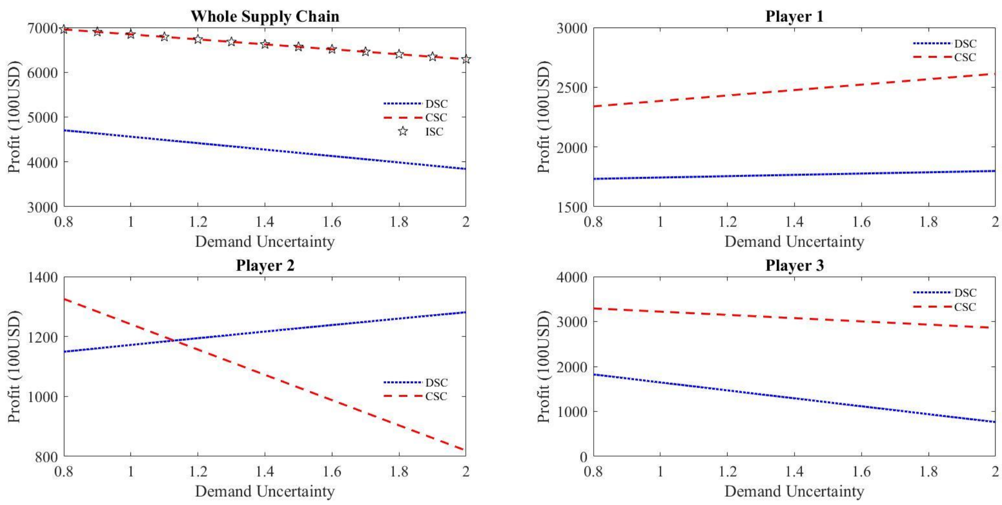

Figure 4. Trends of profitability with different demand uncertainty

Alt Text: The profitability of the coordinated model equals that of the integrated model but exceeds that of the decentralized model with increasing demand uncertainties. A Pareto improvement can be achieved by comparing the profits between the decentralized and coordinated models.

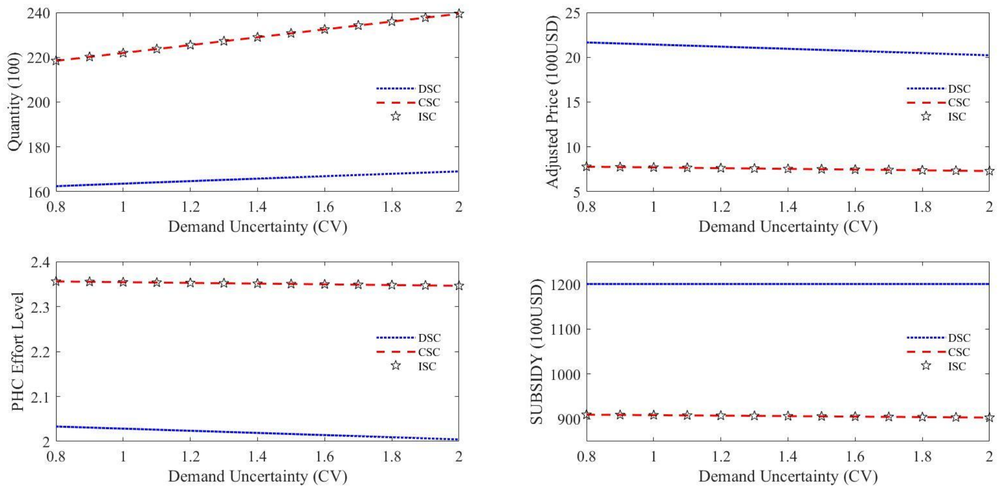

Figure 5. Trends of KPIs with different demand uncertainty

Alt Text: the trends in quantity, adjusted price, PHC efforts and subsidy are given with increasing demand uncertainties.

Figures 6 and 7 indicate the trends of profitability and KPIs of three PHC models with increasing healthy inclination, respectively. Healthy inclination b_b refers to customers' behaviours, attitudes, or practices that promote public health. Figure 6 shows that the PHC benefits from increasing healthy inclination and can achieve full coordination through the proposed contracts. The profits of the whole PHC, Players 1 and 3 increase. The growth rates of profits of the whole PHC and Player 3 gradually slow down as the subsidized PHC costs go beyond the budget. The coordinated profitability of Player 3 experiences an increase and then a decrease as Player 2 shares parts of the PHC costs of Player 1, which are not covered by the subsidy budget. Pareto improvement is achievable through contracts in most cases. However, Player 2 in the coordinated PHC will earn less than the decentralized profit after 12.4, where the coordinated PHC has to adjust the contract settings for Pareto improvement. Figure 7 demonstrates similar results as the numerical study, which states that the coordinated PHC can achieve better KPIs. Both quantities and prices rise with increasing healthy inclination. This indicates that customers with a higher health inclination are willing to pay more for goods with health certifications, leading to a higher volume of orders. Moreover, local businesses will invest more in PHC measures for a healthier environment as well as greater customers' confidence in public health. Hence, intervening to influence healthy inclination may be a challenging but more efficient way of achieving both profitability and public health.

Findings 2: The PHC under different market settings achieve similar results as the numerical case: (1) coordination contributes to higher profitability, a healthier environment, more purchasing power and a better life for the general public; (2) Coordinated PHC requires less subsidy, and thus the saved money can be used to better recover people's normal life. Also, Pareto improvement is achievable through the proposed contracts in most cases, otherwise, the PHC supply chain members would redesign their contracts for win-win conditions. Intervening to influence healthy inclination may be a challenging but more efficient way of achieving both profitability and public health.

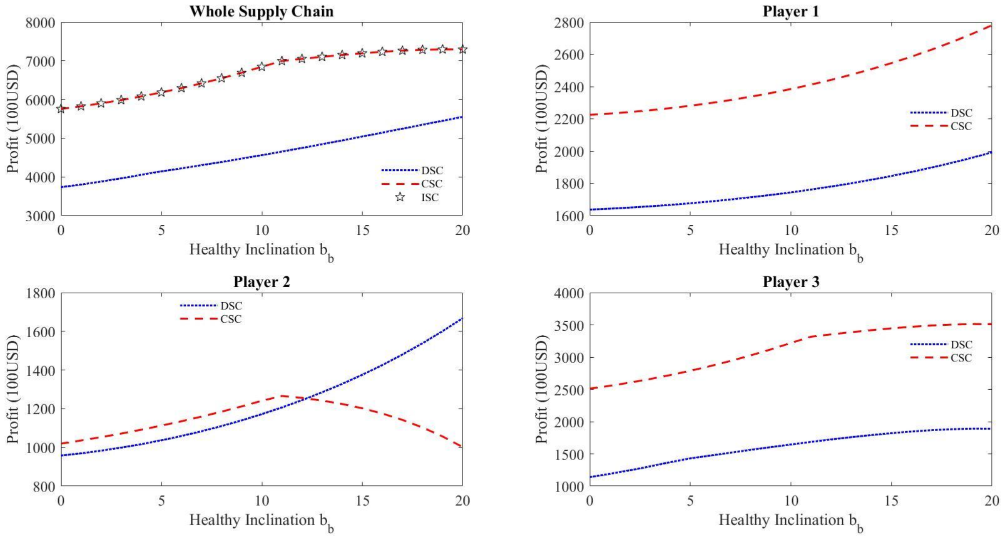

Figure 6. Trends of profitability with increasing healthy inclination

Alt Text: The profitability of the coordinated model equals that of the integrated model but exceeds that of the decentralized model with increasing healthy inclinations. A Pareto improvement can be achieved by comparing the profits between the decentralized and coordinated models.

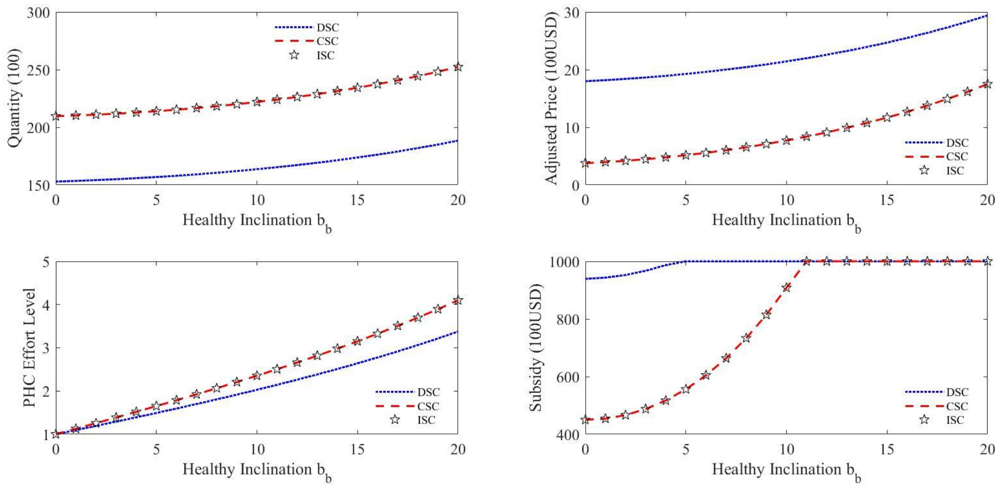

Figure 7. Trends of KPIs with increasing healthy inclination

Alt Text: the trends in quantity, adjusted price, PHC efforts and subsidy are given with increasing healthy inclinations.

Figure 8 illustrates the profitability trends with increasing subsidy budgets. The profitability of the entire supply chain initially increases and then stabilizes as subsidies rise. The profits of Players 2 and 3 follow similar trends, while that of Player 1 remains stable since the subsidy budgets do not cover the PHC costs of Player 1. From the lower left picture of Figure 8, subsidy budgets are more crucial for Player 2 to achieve Pareto-improved coordination. When no subsidy is provided as $M = 0$, the coordinated supply chain can achieve the integrated profit, which is much larger than the decentralized one. Players 1 and 3 can achieve Pareto-improved performance, while the coordinated profit of Player 2 is much lower than its decentralized profit. The lower boundary of the subsidy budget is about 700 under this dataset. Decentralized profits surpass coordinated profits if subsidy budgets are insufficient. The reason is that Player 2 should afford the PHC costs of Player 1, which cannot be subsidized in the coordinated model. When the subsidy budget is sufficiently large $M = 950$, aligning with the scenario without a budget, the performance of all members and the supply chain remains stable.

Findings 3: Adequate subsidy budgets are essential to raise profitability and relieve pressure on supply members, but excessive subsidies lack lasting impact.

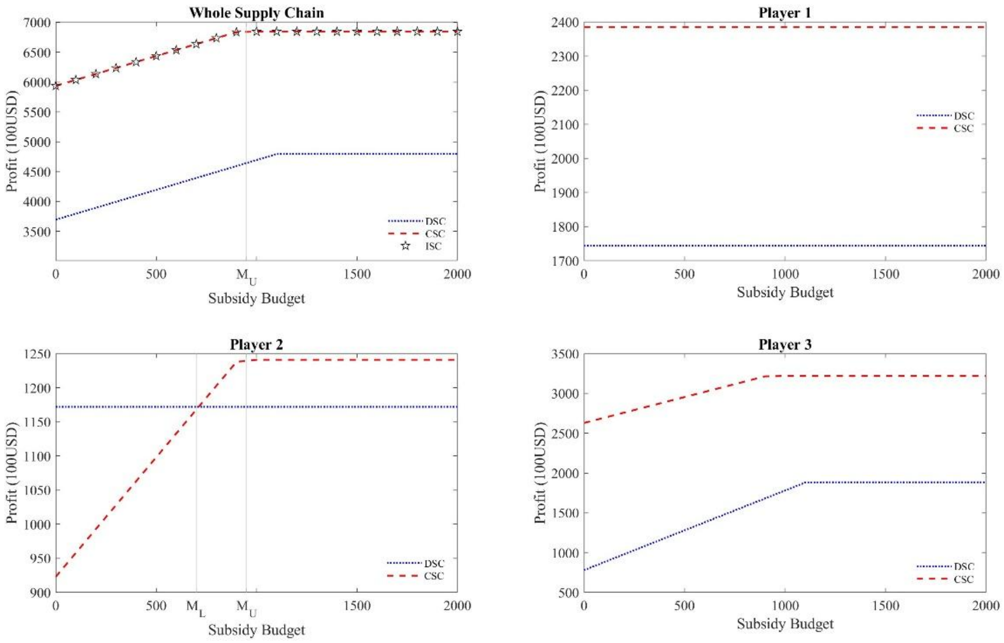

Figure 8. Trends of profitability with increasing subsidy budgets

Alt Text: The profitability of the coordinated model equals that of the integrated model but exceeds that of the decentralized model with increasing subsidy budgets. A Pareto improvement can be achieved by comparing the profits between the decentralized and coordinated models.

The above figures show that Pareto improvement may not be achieved as the coordinated profits of Player 2 are sometimes less than its decentralized profits. One solution is to redesign the contract settings including the cost-sharing and revenue-sharing ratios, which determine the profit distribution among PHC players. Additionally, an extra subsidy from regulatory bodies can be provided for logistics service providers (Player 2), because the proposed cost-sharing contract promises that Player 2 afford parts of the PHC costs of Player 1, which are out of the original subsidy scope. Figure 9 imposes an extra subsidy that will cover 60% of the sharing parts of PHC costs of Player 2. Obviously, the coordinated profits of Player 2 surge up and become larger than the decentralized ones. Pareto improvement is achieved in most market settings, including scenarios with increasing demand uncertainties and healthy inclinations. More subsidy is used if the market is more volatile or if customers are more sensitive to public health. It is around 400-500 (100 USD) with an extra sharing ratio of 0.65.

Findings 4: Regulatory bodies can provide an extra subsidy for logistics service providers to relieve their financial pressures from cost-sharing contracts. This subsidy can bring about constant Pareto improvement and avoid risks of being rejected by PHC players.

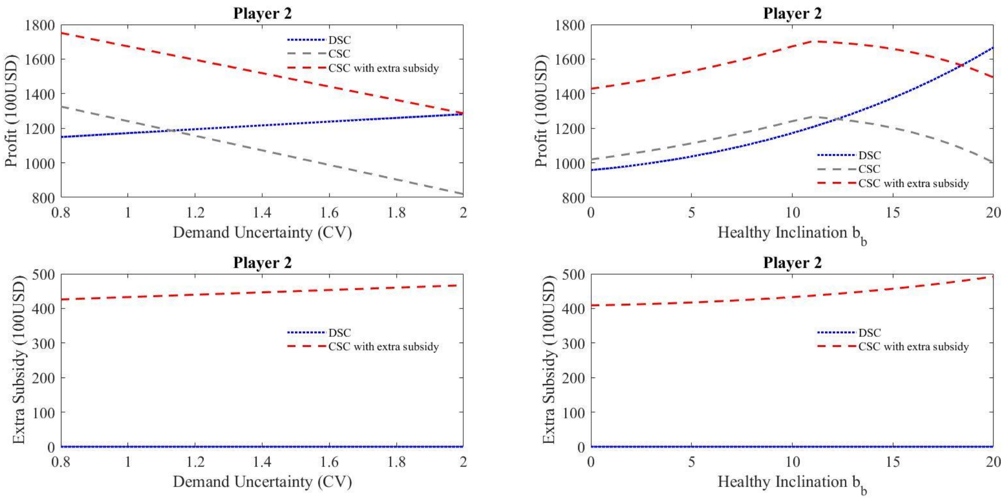

Figure 9. Pareto Improvement with an extra subsidy for Player 2

Alt Text: The trend in profitability and extra subsidy are given with increasing demand uncertainties and increasing healthy inclinations, respectively.

4.2.2 Sensitivity Analyses to contract settings

This section elaborates on the profitability and KPIs of three PHC models under different contract settings, including cost-sharing ratios, revenue-sharing ratios, and adjusted wholesale prices, with the aim to verify their impacts on PHC performance and explore boundaries for Pareto improvement.

As shown in Figure 10, the changes in cost-sharing ratios do not influence PHC coordination efficiency but determine the profit distribution between the exporter (Player 1) and the logistics service provider (Player 2). The profitability of Player 1 increases while that of Player 2 decreases with growing cost-sharing ratios. From the upper right picture of Figure 10, the lower boundary of cost-sharing ratios is 0.548 for Pareto improvement. After 0.548, the coordinated profits of Player 1 surpass those in the decentralized settings. Moreover, Player 1 will engage in cost-sharing as it results in higher profits compared to without cost-sharing. From the lower left picture of Figure 10, the upper boundary of cost-sharing ratios is 0.662. Beyond this point, Player 2 achieves Pareto improvement and is likely to engage in the cost-sharing contract. Under this dataset, the range of cost-sharing ratio for Pareto improvement is $\gamma \in [0.548, 0.662]$, which is discussed in Proposition 2.

Figure 11 indicates that the changes in revenue-sharing ratios do not influence PHC coordination efficiency but decide the profit sharing between the logistics service provider (Player 2) and the importer (Player 3). Player 2 will obtain more profits while Player 3 earns less when the revenue-sharing ratio increases. From the trends of profitability of Players 2 and 3, the range of revenue-sharing ratio for Pareto improvement is $\vartheta \in [0.345, 0.463]$ under this dataset.

Findings 5: Both the cost-sharing and revenue-sharing ratios do not influence the coordination efficiency of the PHC. However, they both determine the profit sharing among PHC players, which is crucial to the contract implementation. Only when all PHC players benefit from coordination, can the proposed contracts be practically performed.

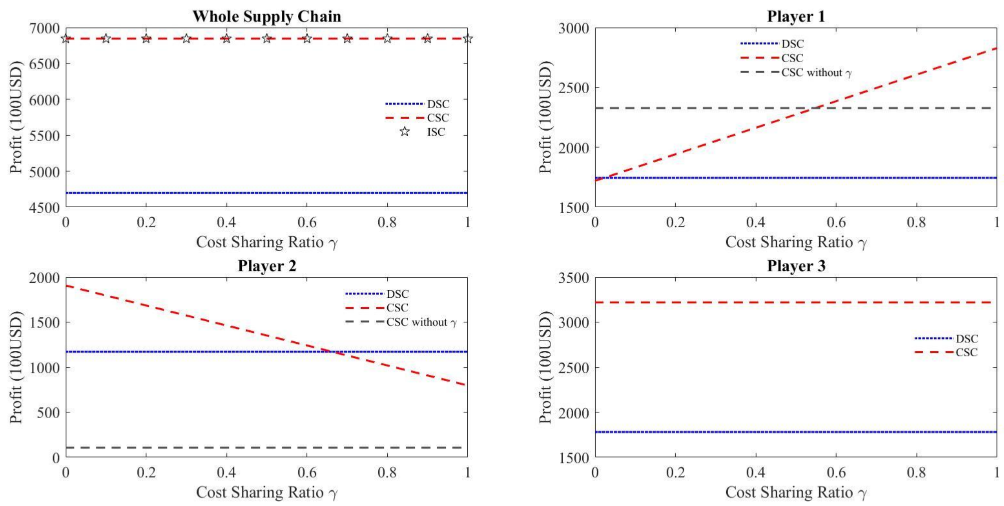

Figure 10. Trends of profitability with increasing cost-sharing ratios

Alt Text: The profitability of the coordinated model equals that of the integrated model but exceeds that of the decentralized model with increasing cost-sharing ratios. A Pareto improvement can be achieved by comparing the profits between the decentralized and coordinated models.

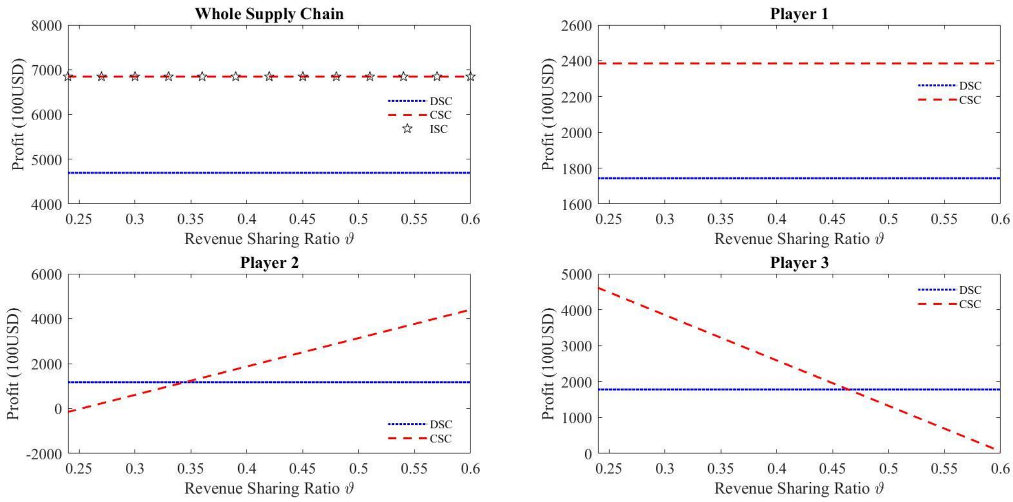

Figure 11. Trends of profitability with increasing revenue-sharing ratios

Alt Text: The profitability of the coordinated model equals that of the integrated model but exceeds that of the decentralized model with increasing revenue-sharing ratios. A Pareto improvement can be achieved by comparing the profits between the decentralized and coordinated models.

Figures 12 and 13 present the trends of profitability and KPIs of PHC with increasing adjusted wholesale prices. From Figure 12, the adjusted wholesale price does affect the coordination efficiency as well as the profit distribution. The PHC can be fully coordinated when the adjusted wholesale price satisfies $w_m + \omega = c_s + c_m + h_s = 30$, otherwise, partial coordination is achieved. The profits of Players 1 and 3 decrease while that of Player 2 increases with growing adjusted wholesale prices. Pareto improvement is achievable when the adjusted wholesale price is within $w_m + \omega \in [29.7\,, 40.4]$.

Figure 13 shows that the order quantity, PHC efforts, and subsidy used decrease, while adjusted price increases with increasing adjusted wholesale prices in the coordinated PHC. When the adjusted wholesale price is 30, these KPIs are equal to the integrated results. If the wholesale price remains the original 60, the coordinate KPIs, excluding the subsidy used, are equal to the decentralized ones. At 60, the PHC is collaborated by the cost-sharing and revenue-sharing contracts, and thus its profitability achieves better performance, and the subsidy used is less than the decentralized one. Without the wholesale-price contract, the revenue-sharing and cost-sharing contracts can drive the profitability up and save some subsidy. In conclusion, the wholesale-price contract plays an important role in achieving better KPIs, which results in a healthier environment where customers possess larger purchasing power and bear less financial burden from increased prices.

Findings 6: The contract-makers should deliberate the contract settings to achieve better PHC performances. Well-designed contracts benefit all PHC stakeholders and will bring our society back to normal as soon as possible.

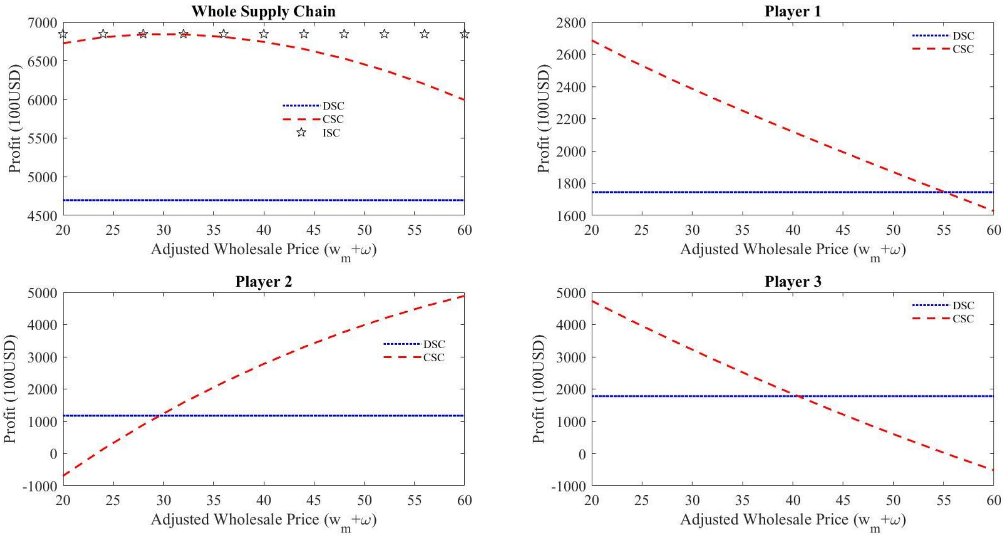

Figure 12. Trends of profitability with growing adjusted wholesale prices

Alt Text: The profitability of the coordinated model equals that of the integrated model but exceeds that of the decentralized model with increasing adjusted wholesale prices. A Pareto improvement can be achieved by comparing the profits between the decentralized and coordinated models.

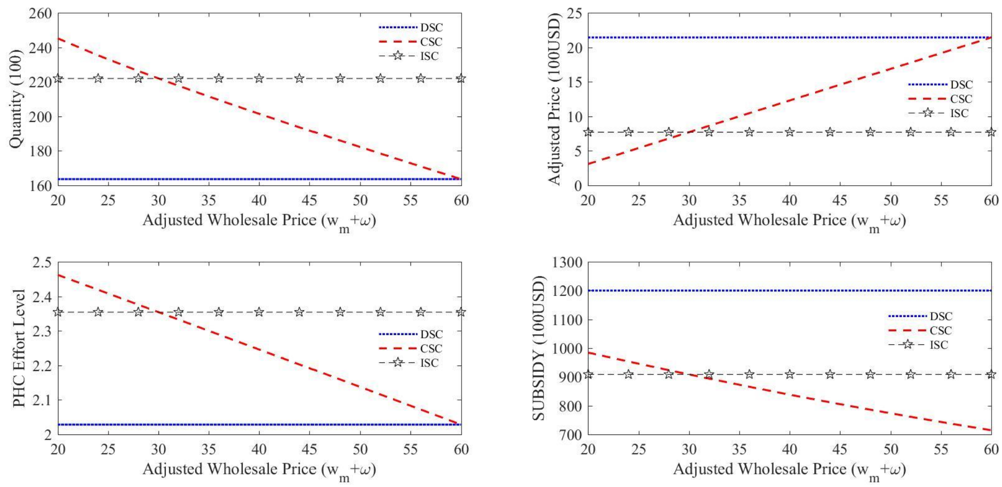

Figure 13. Trends of KPIs with growing adjusted wholesale prices

Alt Text: the trends in quantity, adjusted price, PHC efforts and subsidy are given with increasing adjusted wholesale prices.

V. IMPLICATIONS FOR PHC CONFIGURATION

Considerable global supply chains are disrupted by virus transmissions without PHC. We have proposed two levels of global supply chain PHC, the basic and advanced levels, to reopen the port and border crossings for smooth and healthy supply chain operations and to theoretically identify how close new norms are to the norm. According to the theoretical and numerical results with corresponding propositions and findings, this section derives and formulates policy and managerial implications for implementing global supply chain PHC.

The performances of the basic level of PHC (decentralized model) studied before indicate that the global supply chain operations resume with consistent and appropriate measures on COVID-19 prevention, although the fears and burdens from the COVID-19 pandemic incur negative impacts on profitability, customer maintenance, and price competitiveness, as well as the well-being of individuals. The basic PHC achieves 163.597 quantity, approximately 65% of the normal quantity before the COVID-19 crisis (See Table 6). The establishment of the basic global supply chain PHC basically solves the dilemma between public health and smooth supply chain operations. As discussed in the mathematical study, all the players have to invest in compulsory pandemic control measures, like vaccines, temperature checks, health declaration, disinfection, etc. Some of them (H_s , H_m , and H_b) are related to the number of visited personnel. Hence, the business could carefully limit the number of visited workers and guests for smaller costs on this kind of basic pandemic control measures.

Recall the concept of PHC (shown in Figure 1) and Assumption 1, PHC efforts to achieve COVID-19 negative reports and labels are crucial for reopening borders. Goods without health certificates will be refused entry at ports and borders. Furthermore, Finding 1 shows that decentralized PHC can partially restore global supply chain operations.

Policy Implication 1: The implementation of the basic level of PHC has the potential to resume global supply chain operations with consistent and appropriate COVID-19 control measures, although the fears and burdens from the COVID-19 pandemic incur negative impacts.

Policy Implication 2: Mutually recognised COVID-19 negative reports and labels are crucial to the imported goods freely entering ports and borders with healthy certificates, which allow them to be traded in the importing market and create more confidence in public health.

The global supply chain members should comply with PHC regulations set by regulatory bodies, which determine whether imported goods can enter the borders (See Table 6, Finding 1, and Figure 1).

Both mathematical and numerical analyses indicate that imported goods can freely enter the borders when sufficient PHC measures are implemented, as $i_s + i_m = 1$. Findings 3 and 4 show that reducing PHC costs increases profitability. This can be achieved by minimizing the number of visited workers and guests in addition to subsidy programs.

Managerial Insight 1: Supply chain members should follow PHC regulations for freight logistics to assure authorities that imported goods can freely enter the borders.

Managerial Insight 2: Businesses can recover their international trading through joining the PHC system. They can carefully limit the number of visited workers and guests to reduce the costs of basic pandemic control measures.

The advanced level of PHC aims to establish better conditions for ending COVID-19 transmission across global supply chains and achieving optimal performance of global supply chain operations through contract-based government-private-public partnerships (G3P). As discussed in mathematical and numerical results, it achieves 221.4994 quantity, approximately 89% of the norm before the COVID-19 crisis, bringing the operations back to near-normal (See Table 6). The coordinated PHC achieves superior results compared with the basic level, including higher profitability, greater price competitiveness, and better customer maintenance (See Findings 1 and 2). As shown in Findings 3 and 4, less subsidy is consumed through G3P coordination and the saved money can be used in ways to better recover normal operations. Governments and communities can provide other subsidy schemes encouraging PHC players to participate in the G3P coordination, like additional PHC subsidies, cash payout schemes, tax reduction schemes, etc. Also, interventions to strengthen healthy confidence, like propaganda or relaxation of gathering bans, can be conducted by the governments and/or communities. It may be a challenging but more efficient way of achieving both profitability and public health.

Policy Implication 3: The launch of the advanced level of PHC with well-designed G3P strategies effectively improves the performances of healthy supply chains and the well-being of individuals and communities. The coordinated PHC would allow freight logistics to perform with minimal additional burdens while maintaining freight safety and preventing COVID-19 transmissions.

Policy Implication 4: Government and/or communities can provide PHC subsidies for the recovery of global supply chain operations. They can also encourage PHC players to participate in the G3P coordination through tax reduction or other subsidy schemes. Moreover, their guidance on healthy confidence and purchasing habits is vital for the effective launch of coordinated PHC.

Findings 1, 2, 5, and 6 demonstrate that proper contracts can enhance profitability and achieve Pareto improvement. All supply chain members benefit from the G3P strategies, under which coordinated supply chain operations have the potential to approach near-normal levels. The optimal settings for cost-sharing ratios, revenue-sharing ratios, and adjusted wholesale prices are correspondingly provided. Under these optimal contract settings, supply chain members raise profits, offer lower prices, and achieve larger quantities. Since PHC costs significantly influence the profitability of supply chain members, as shown in Figures 8 and 9, subsidies reduce the PHC burden on supply chain players (as demonstrated in Findings 3 and 4). Besides subsidies, PHC players can negotiate with third-party agencies to lower the costs of COVID-19 testing and inspection through methods such as package deals or group buying. This will relieve the financial pressures of the businesses and achieve better profitability.

Managerial Insight 3: All the stakeholders in PHC should take into consideration G3P strategies to achieve optimum conditions for establishing new norms for global supply chains to function near-normally.

Managerial Insight 4: The PHC players can take advantage of properly designed contracts to stay competitive on profitability, price, and customer maintenance. In addition to receiving subsidies to reduce PHC costs, PHC players can negotiate with third-party agencies for lower COVID-19 testing and inspection costs through package deals or group buying.

VI. CONCLUSION

This research aims to effectively build global supply chain public health corridors (PHC) through contract-based government-private-public partnerships (G3P), and further create new norms for global supply chains facing potential disruptions out of the COVID-19 crisis. Since the COVID-19 outbreaks, the public is of course concerned with the potential of spreading viruses adhere to surfaces of freights through global supply chains. Besides, the businesses inside supply chains are concerned with the costs of assuring COVID-19-free delivery and the potential disruptions associated with the importing bans of COVID-19-suffering countries. Thus, the global supply chain PHC are proposed to address the dilemma between health conditions and normal supply chain operations with harmonized hygiene standards and consistent and appropriate COVID-19 border measures.

This research introduces a novel approach to coordinating a three-tier supply chain for preparation, response, and recovery during disruptions through PHC implementation. It addresses a critical research gap by proposing strategies to sustain social and economic activities with minimal burden. Numerical and analytical results indicate that PHC successfully resumes the global supply chain operations although the pandemic incurs negative impacts on its performance. Fortunately, a well-designed G3P mechanism contributes to optimum conditions with minimal additional burdens for ending COVID-19 transmission and achieving better results in profitability, all other KPIs, and the well-being of the public. All the stakeholders have incentives and are encouraged to join in the advanced level of PHC through a properly designed G3P mechanism. The establishment of PHC would bring global supply chain operations back to near-normal as soon as possible and direct international trading along with a smooth, sustainable, and virus-free trajectory.

While this study presents significant advancements, several limitations still exist. Notably, opportunities should be acknowledged for further research due to the lack of literature on supply chain operations under COVID-19 hardships. First, harmonized hygiene standards and consistent, appropriate measures have not yet been set, which can be deeply studied by experts and scholars in the future. Second, other G3P strategies can be explored by combining different social and economic conditions. For example, supply chain players can adopt other contracts for coordination, and governments and/or communities can provide various kinds of subsidies or preferential policies to facilitate PHC construction. Third, this research examines a three-tier supply chain with a linear demand function. Real-world scenarios typically feature dynamic conditions and varying demand functions, which future models should incorporate for greater realism and applicability. Additionally, global supply chains with more complicated structures deserve further discussion to practically launch the PHC. Last but not least, this research only considers supply chain disruptions caused by sporadic yet prolonged COVID-19 outbreaks; other unexpected events can be taken into consideration for future work.

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Data Availability Statement

Data available within the article or its supplementary materials.

Disclosure of Interest

The authors report there are no competing interests to declare.