



Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.



ELSEVIER

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Transportation Research Part E

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

A multi-period multi-modal stochastic supply chain model under COVID pandemic: A poultry industry case study in Mississippi

Amin Yazdekhasti^a, Jun Wang^b, Li Zhang^b, Junfeng Ma^{c,*}

^a Department of Industrial Engineering, Daneshpajooan Pishro Higher Education Institute, Isfahan, Iran

^b Department of Civil and Environmental Engineering, Mississippi State University, Mississippi State, MS 39762, USA

^c Department of Industrial and Systems Engineering, Mississippi State University, Mississippi State, MS 39762, USA

ARTICLE INFO

Keywords:

Poultry supply chain
Covid-19
Multi-modal networks
Stocking policy
Branch and Cut
Mississippi poultry industry

ABSTRACT

The poultry industry is one of the most important agricultural sectors, which constitutes a significant part of the per capita consumption of protein and meat. Integrating operations of poultry industry sections including production, distribution and consumption becomes vital. Although the proper poultry supply chain has been established and made plenty of benefits for a long time, the global outbreak of COVID-19 shows that operations under pandemic are still challenge for the poultry industry. In this paper, the impacts of pandemic on poultry industry is investigated by developing a multi-period multi-modal stochastic poultry supply chain. Two models are developed aiming to mitigate the negative effects of pandemic occurrence through product stocking policy. In the first model, distribution system is in accordance with a multi-component structure, while the second model allows direct connections between suppliers (farmers) and demanders (customers). In both models, poultry productions are negatively affected by COVID 19. Due to the complexity of the model, a hybrid solution approach based on Branch and Cut and Dynamic Programming is developed. To validate the performance of the proposed model and solution procedure, a case study on the broiler industry in the state of Mississippi is performed. The results show that storing poultry products in the pre-pandemic along with direct logistics during pandemic period can save the broiler supply chain cost up to 30%.

1. Introduction

Poultry industry is one the largest commercial sectors in the agriculture commodities in the world. According to the National Chicken Council report, poultry industry in the U.S. provides 1,682,269 jobs, \$441.15 billion in economic activity, and \$34 billion in government revenue (National Chicken Council, 2020). In the state of Mississippi which is the fourth largest poultry producer in the US, there are 1,700 family-run poultry farms (MS Poultry Association, 2020), which not only support domestic customers, but also play a key role in broiler meat export to Mexico, Cuba and Taiwan (US Poultry, 2020). Given this scale, ensuring the resilience of poultry industry is extremely important. Having a synchronized supply chain system that incorporating the poultry farmers' production policies, distribution channels and customer demand satisfaction can maintain the resilience and profitability of the whole poultry industry (Kalhor et al., 2016).

* Corresponding author.

E-mail addresses: yazdekhasti@daneshpajooan.ac.ir (A. Yazdekhasti), jwang@cee.msstate.edu (J. Wang), lzhang@cee.msstate.edu (L. Zhang), ma@ise.msstate.edu (J. Ma).

<https://doi.org/10.1016/j.tre.2021.102463>

Received 3 January 2021; Received in revised form 9 August 2021; Accepted 17 August 2021

Available online 28 August 2021

1366-5545/© 2021 Elsevier Ltd. All rights reserved.

Recently, one of the most significant challenges in the poultry supply chain is the catastrophic impact of COVID-19 (Antipova, 2020). COVID-19 will certainly not be the last “black swan” event, and the entire poultry industry will be paralyzed if production and distribution policies are not prepared to deal with such pandemics. COVID-19 has severe negative impacts on poultry industry, which creates several significant challenges for different segments of its supply chain. From the manufacturer perspective, the decline of consumption demand leads to the reduction of poultry production. According to National Agricultural Statistics Service (USDA-NASS), in U.S., broiler chicks hatched were 5.6% and 5.9% lower in April and May 2020, compared with the same months a year ago. From the social perspective, chicken plant workers are at risk of infection by COVID-19. For example, 1438 confirmed cases were recognized among chicken plant workers in Mississippi and 25 of them were passed away until Nov. 17, 2020. From the logistic perspective, COVID-19 pandemic leads to the lockdown in the supply market and interruption in the transportation system. The global chicken meat trade declined by 4% due to the impact of COVID-19 on poultry supply chain (Das & Samanta, 2021).

COVID 19 pandemic has resulted in different consequences of poultry industry supply chain segments depending on the severity. Pandemic will affect poultry production rate (Kolluri et al., 2021; Palouj et al., 2021), customer access and demands (Kolluri et al., 2021; Uyanga et al., 2021) and transportation (Uyanga et al., 2021). The more severe of pandemic, the lower production rate, customer access/demands, and transportation availability. Therefore, depending on the pandemic severity, poultry supply chain needs to take corresponding activities to mitigate the pandemic’s impacts. There is an urgent need to investigate how to adjust poultry supply chain strategies under COVID-19 pandemic, which motivates this study.

Due to the significant impact of pandemic (e.g., COVID 19, poultry diseases) on poultry supply chain, many studies were conducted to investigate how to mitigate the negative impacts. For example, Le Hoa Vo & Thiel (2011) proposed a simulation model to analyze the French chicken meat production under decrease. Parvin et al. (2018) provided a review analysis of effect of co-circulating H5N1 and H9N2 avian influenza viruses on poultry production in Bangladesh. However, these studies focused on part of supply chain, such as production, and neglected the other segments in the supply chain. In this paper, we investigate the effect of pandemic on the entire poultry industry supply chain by implying a stochastic two-stage multi-modal multi-period model. To synchronize the cooperation among farmers, customers and distributors, a poultry supply chain strategy is designed in which farmers serve both domestic and international customers through a multi-modal hub distribution network. To study the potential effect of pandemic (e.g., COVID 19) on the proposed poultry supply chain, the problem has been divided into different periods in which farmers’ capacity and customers’ demand vary periodically. In each period, there is a chance of pandemic and its severity can be different. To mitigate the effects, the policy of stocking farmers’ products in hub facilities during pre-pandemic period is investigated. This storage policy, on the one hand, allows farmers to keep their sale power under difficult pandemic conditions, and on the other hand, satisfies customers in these periods. Since solving the proposed model using commercial solution software is time consuming, a customized hybrid solution procedure is developed based on Branch and Cut algorithm and dynamic programming approach. A case study is conducted in the state of Mississippi’s broiler industry to evaluate the proposed model and solution approach.

Our paper has multiple contributions. First of all, from the theoretical perspective, this paper 1) considers inventory control policy in the hub facility management. In the most of existed logistic studies and especially the hub location problems, hub centers only perform collecting, sorting and distributing duties. Although these activities could reduce the total amount of direct paths from origin/destination pairs, they do not support suppliers during the pandemic. The storing activities/inventories in the hub facilities allow the suppliers to have ample opportunities in the pre- and early-pandemic periods to meet their customers’ demands during the pandemic period; 2) introduces a multi-modal transportation system considering land, rail and water ways to optimize large scale poultry distribution system; and 3) considers the impacts of severity of pandemics on farmers’ production rate, multi-modal transportation system operations, and access of customers.

Furthermore, from the perspective of methodology, this paper 1) develops an efficient hybrid solution approach based upon Branch & Cut and Dynamic Programming approaches to optimize the proposed poultry supply chain model; and 2) determines the tight upper and lower bounds through expanding Variable Neighborhood Search algorithm and multi-stage relaxations procedure.

Additionally, this paper also contributes to practical implementations, including 1) providing optimal distribution strategies for logistics companies to support farmers during pandemics while controlling their cost and 2) being able to expand the implementations to similar food supply chains such as pork and beef to mitigate the negative impacts under pandemic.

2. Literature review

The poultry industry plays the significant role in the health and economy sections around the world. The poultry meat has the highest protein efficiency compare with other meat sources, and 19.4% of protein in poultry feed inputs are effectively converted into poultry products (Ritchie & Roser, 2017). Because of its nutritive advantages, the global poultry market is growing and estimated as \$322.55 billion in 2021 (Researchandmarkets, 2021). Hence, poultry industry and its relevant supply chain become popular and attract growing attentions in the academia.

The supply chain resilience receives significant attentions recently (Amrani et al., 2021). The investigation of supply chain resilience can be categorized depending on whether the crisis/uncertainty involved (e.g., Park et al., 2018; Alizadeh et al., 2019a, 2019b). Poultry supply chain is not an exception. The existing poultry supply chain studies can be clustered into two groups based on the involvement of crisis, the first group of studies is investigating the supply chain under normal circumstances without the sign of crisis (e.g., Ghozzi et al., 2016; Tsolakis et al., 2018; Xiao et al., 2019; Chaudhry & Miranda, 2020). The investigation approaches include mathematical modeling and optimization (e.g., mixed integer linear programming, multi-objective programming, mixed integer programming, integer programming, etc), and simulation. Among them, Sebatjane & Adetunji (2020) designed a three-echelon poultry supply chain network including farming, processing, and consumption (retail) components. Their proposed model showed that

Table 1
Literature review summary.

Paper	Seasonal variation	Poultry disease effect	Pandemic effect	Mathematical	Logistic	Demand nature	Multi-period	Multi-modal	Multi-echelon	Explanations
Le Hoa Vo & Thiel (2011)		✓				Deterministic	✓			Simulation/System dynamics
Ala-Harja & Helo (2014)				✓	✓	Deterministic				Greenhouse emission controlling
Balaman & Selim (2014)				✓	✓	Deterministic	✓		✓	Anaerobic digestion systems
Ghozzi et al. (2016)					✓	Deterministic				Transaction cost approach/resource-based view
Mogale et al. (2018)				✓	✓	Deterministic	✓	✓		Model grain silo location-allocation problem
Tsolakis et al. (2018)						Deterministic	✓			System dynamics
Chowdhury & Morey (2019)						Deterministic				QR code
Wu et al. (2019)	✓	✓		✓	✓	Deterministic	✓✓			Cross-sectional surveys
Xiao et al. (2019)				✓						Predictive models
Amankwah-Amoah (2020)			✓		✓					Greenhouse emission controlling
Aslam et al. (2020)		✓				Deterministic				Value chain maps
Brevik et al. (2020)				✓	✓	Deterministic	✓			Rolling horizon heuristic
Chaudhry & Miranda (2020)				✓	✓	Deterministic	✓			Error-correction model
Gital Durmaz & Bilgen (2020)				✓	✓	Deterministic	✓			Analytical hierarchy process
Govindan et al. (2020)			✓		✓					Decision support system to manage healthcare SC
Ivanov (2020)			✓		✓					Investigating the effect of outbreaks on global SC
Maples et al. (2020)			✓	✓	✓	Deterministic	✓			Static and stochastic budget analyses
Maslova, et al. (2020)						Deterministic	✓			Survey and data collection
Singh et al. (2021)			✓		✓					Conceptual method
Sebatjane & Adetunji (2020)				✓	✓	Deterministic	✓		✓	Heuristic/Inventory control
Unveren & Luckstead (2020)				✓	✓	Deterministic	✓✓			Theoretical model and numerical analysis
Weersink et al. (2020)			✓							Data analysis
Choi (2021)			✓		✓					Studying different aspects of risk in logistic systems during and after COVID-19
This study	✓	✓	✓	✓	✓	Stochastic	✓	✓	✓	Hybrid algorithm based on Branch & Cut and Dynamic programming

customer demands are largely dependent on the selling price and the expiration date. Unveren & Luckstead (2020) proposed a simulation model for analyzing the US broiler industry under corn and soybeans tariff imposed by China and the variation of the Canadian tariff-rate quota proposed by Mexico–Canada–Agreement. To make the appropriate decisions about bio-poultry-mass supply and product distribution, Balaman & Selim (2014) developed a mixed integer linear programming model to optimize the locations of biogas plants and biomass storages in order to have an effective poultry supply chain network. Ala-Harja & Helo (2014) studied the impact of greenhouse emission controlling policies on food sections, especially the poultry industry, from the perspectives of order-picking, distribution and transportation. Mogale et al. (2018) proposed a multi-objective, multi-modal, multi-period model to study grain silo location-allocation problem to help government of India controlling poultry shortage. Gital Durmaz & Bilgen (2020) investigated the designing and planning of the bio-poultry-mass supply chain network by means of a multi-objective mixed linear programming model in Turkey. Brevik et al. (2020) applied a mixed integer programming model to optimize Norwegian broiler supply chain by determining the optimal schedule of broiler production, chicken flock size and reducing the allowed age difference between parent hens for each chicken flocks.

The second group of poultry supply chain literatures studied the destructive effects of crisis factors such as seasonal variation, poultry diseases and outbreak of pandemics on the supply chain. These factors include a wide range of damages from farmer's production fluctuations by seasonal changes to severe damages such as the death of millions of poultry due to Avian influenza (AI) or irreparable damages such as death of thousands of poultry workers and loss of billions of dollars by pandemics outbreaks (Kalhor et al., 2016; World Bank, 2005; Kolluri et al., 2021). Among these studies, Barnes et al. (2019) developed a stochastic mathematical model to formulate the risk impact of HPAI in the commercial poultry industry. Later, Scott et al. (2020) reviewed all HPAI outbreaks since 1976 in poultry farms and low pathogenic avian influenza (LPAI) cases in Australia. Wu et al. (2019) performed four rounds of cross-sectional surveys to study AI spread in poultry supply chain sections in Guangdong, China using logistic regression. The results indicated that since there is a transmission risk to human, the poultry supply chain should be closely monitored. Aslam et al. (2020) characterized the chicken industry in Pakistan based on detailed value chain maps and added the role of health service providers to suppress poultry diseases.

Although AI has had devastating effects on the poultry supply chain, the occurrence of pandemics such as COVID-19 can have far more irreversible effects. As of Aug. 2020, there were approximately 50,000 cases among poultry workers in Brazil. In India, COVID-19 caused \$3 million loss in poultry industry (Kolluri et al., 2021). Several latest studies future investigated how the COVID-19 affects poultry supply chain. Waltenburg et al. (2020) reported the impact of COVID-19 on the workers in meat and poultry processing industry in U.S. Hafez & Attia (2020) investigated the current and future challenges imposed by COVID-19 outbreak on poultry industry. They concluded that new supply chain operational strategies are needed to mitigate the disease impacts on the poultry industry. Esiegwu & Ejike (2021) studied the poultry production under COVID-19 in south-east agro-ecological zone of Nigeria using multistage and purposive sampling technique. The results showed that the COVID-19 led to shortage in feed ingredients and increased the price. Consequently, the production cost and selling prices were increased which imposed high pressure to poultry meat consumers. Weersink et al. (2020) studied how COVID-19 has impacted the poultry supply chain in Canada between the period of December 2019 and March 2020 and suggested two major strategies. Firstly, the automation level should be increased during production process to reduce the amount of dependence on manpower. Secondly, poultry production should be localized to decrease the degree of dependence on global suppliers. The suggestions may help to decrease the negative effects of COVID-19, but would create long term consequences like unemployment. Maples et al. (2020) demonstrated how broiler producers have been impacted by COVID-19. Static budget analysis is performed to determine the reduction in net revenue and stochastic budget analysis is conducted to draw the cumulative distribution of net cash flow for a particular number of chicken flocks per year. The model is useful for farmers to estimate their losses due to COVID-19 and accordingly, their search for relief policies will be more realistic.

While most of the current studies endeavor to recognize and approximate the effect of COVID-19 on poultry producers through either simulation approaches or conceptual models, there is an urgent need to focus on the whole poultry supply chain and provide long term strategies that not only mitigate problems of different segments of supply chain, but also do not create new problems like unemployment. Table 1 provides a summary on the reviewed literature. Compared with the literature, this study saves farmers' cost by means of optimal strategies of production and storage during pre and peak of pandemic. Also, this study provides optimal distribution strategies for logistics companies to support farmers during pandemic while control their costs. Finally, this paper brings some clues for similar supply chains such as pork and beef to how mitigate the negative impact of pandemics (i.e. COVID-19).

The rest of the paper is organized as follows: problem statement and mathematical formulation of the poultry supply chain are described in section 3. The proposed hybrid solution approach is described in section 4. Section 5 presents the results of optimizing the broiler supply chain in the state of Mississippi and finally conclusion and future research is explained in Section 6.

3. Problem description and model generation

In this section, problem description will be provided in the first subsection; followed by model assumptions, sets, parameters and variables in the second subsection; then, the mathematical formulation of Model 1 and Model 2 will be introduced in the third subsection.

3.1. Problem description

Consider a poultry supply chain defined by a network of $G = (N, A)$, where N represents a set of nodes and A presents a set of arcs. Set $N = S \cup D \cup H$ contains three subsets: suppliers or farmers (*setS*), customers (*setD*) and distribution centers or hub nodes (*setH*). Arc

set $A = A_1 \cup A_2 \cup A_3 \cup A_4$ includes four sets, A_1 is set of arcs between farmers and hub nodes, A_2 is arc set of inter-hub nodes, A_3 shows set of arcs between hub nodes and customer nodes, and A_4 represents the set of arcs that directly link farmers to customers. To distribute the farmers' products among customers, we propose a multimodal hub location structure in which there are three types of transportation modes ($setP = R \cup V \cup RV$) including rail ($setR$), ship ($setV$) and truck ($setRV$). Farmers should support two types of customers ($setD = DC \cup IC$) in different time periods ($set T$), domestic customers ($setDC$) with constant demand rate and international customers ($setIC$) with stochastic demand. At each period $t \in T$, there is a chance of pandemic which negatively affects production rate, the availability of transportation modes, and access to the customers, depending on the pandemic severity. A farmer should decide sending product to customers either by direct logistic policy along arc $(s, d) \in A_4$ or indirect logistic strategy by using multimodal hub routes $(s, h) \in A_1 \rightarrow (h, h) \in A_2 \rightarrow (h, d) \in A_3$. While under direct logistic policy, only trucks are available; in multimodal hub routes not only all transportation modes can be accessed but also stocking products in hub facilities are available. In the indirect logistic strategy, firstly products are transported from farmers to the origin hub facilities along arc $(s, h) \in A_1$ by truck. Then depending on regional specification, ships or railway fleet carries the collected products from origin hubs to the designation hubs along arc $(h, h) \in A_2$. At the destination hub facilities, to mitigate the effect of pandemic, farmers can stock their products at pre-pandemic periods for supporting their customers during pandemic. It should be noted that since destination hubs are closer to customer zones, selecting them as warehouses is always superior to origin hubs. Finally, the products are delivered to the customers from destination hubs by truck through arc $(h, d) \in A_3$. In addition, farmers' production capacity at each period $t \in T$ is affected by risk of global pandemic such as COVID pandemic. To calculate the farmers' production capacity, Ω defines the scenarios set regarding the production rate of farmers' poultry house with a fixed number of scenarios $|\Omega|$ associated with probability of Pr_{ω} ($Pr_{\omega} \geq 0$).

Therefore, in the first step, the poultry supply chain aims to determine the optimal location of hub facilities in the distribution network and optimally assign farmers and customers to the located hub facilities. In the second step, depending on the pandemic severity at each period, it aims to determine the optimal amount of each farmer's productions that should be delivered to each customer and its optimal logistic policy (direct or indirect). For this purpose, at first, we formulate the poultry supply chain model under pandemic occurrence where only indirect logistic policy is available (Model 1). Then, the initial model will be expanded by having access to both direct and indirect transportation strategies (Model 2). Fig. 1 shows the network configuration of Model 2.

3.2. Mathematical model generation

3.2.1. Assumptions

- 1) There is only one poultry product type.
- 2) At each period, the occurrence of pandemic and its severity are pre-known.
- 3) There is some risk of diseases or global pandemic such as COVID 19, which affects the production rate of farmers.
- 4) International customers' demand at each period is stochastic follows normal distribution.
- 5) Available transportation modes in each path at each period are predetermined.
- 6) Transportation cost is positively related to traveling time among two nodes.
- 7) Farmers cannot send their products to each other.
- 8) Farmers and customers should be allocated to one hub facility.
- 9) Customers can be directly supported by more than one farmer.
- 10) Transporting products from non-hub to hub is performed by trucks and inter-hub routes are served either by ships or rail.

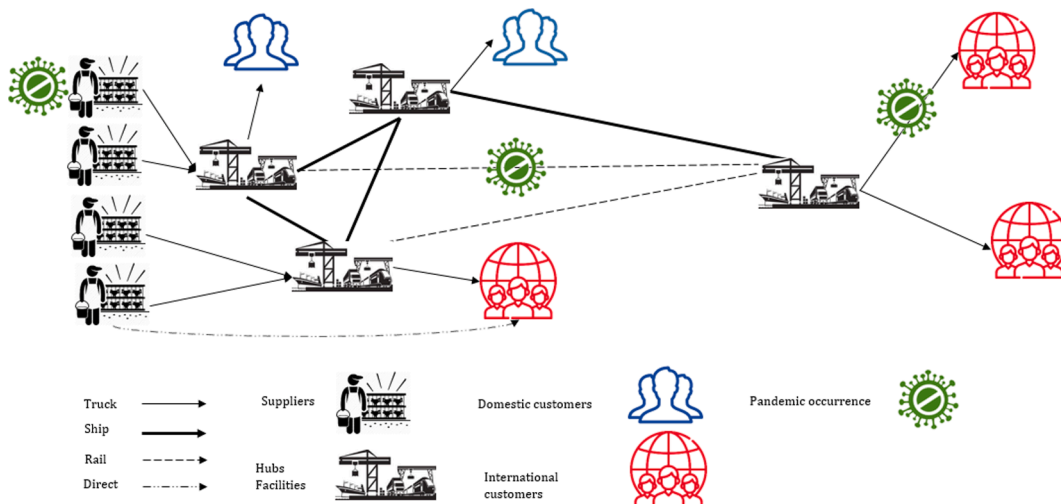


Fig. 1. Poultry supply chain structure under pandemic with access to both direct and indirect transportation strategies.

3.2.2. Notations

Sets, parameters and variables of the model are presented below.

Sets	
N	Set of nodes including farmers, hubs and customers
S	Set of farmers
D	Set of customers $D = \{DC, IC\}$
DC	Domestic customers
IC	International customers
P	Set of transportation modes
R	Set of trains
V	Set of ships
RV	Set of trucks
Ω	Set of scenarios
T	Set of time periods

Parameters

c_{jq}^p	Installation cost of hub $j \in H$ with capacity $q \in Q$ for transportation mode $p \in P$
NHF	Number of hub facilities
t	Time period.
$\mathcal{L}_{ik}(\omega)$	The available number of poultry homes (poultry production line) for supplier $k \in S$ at time period $t \in T$ under scenario $\omega \in \Omega$.
$\dot{Y}_{ik}(\omega)$	The production rate of each poultry home for supplier $k \in S$ at time period $t \in T$ under scenario $\omega \in \Omega$.
$demand_l$	Customer demands $l \in D$ at period $t \in T$ (if $l \in DC$, $demand_l$ is constant and if $l \in IC$, $demand_l$ has stochastic nature).
cap_{ij}^p	Transportation capacity of transportation mode $p \in P$ through path $i \rightarrow j$ at time period $t \in T$.
$Vmax_q^p$	The maximum number of vehicles of transportation mode $p \in P$ with capacity of $q \in Q$.
$ACPE_l^t$	The accessibility level to customer $l \in D$ with respect to pandemic severity, during period $t \in T$
MPE^t	The percentage of production rate that can be accessed during time $t \in T$ regarding the pandemic severity
VPE_p^t	The accessibility level of transportation mode $p \in P$ at period $t \in T$ due to the pandemic effect
μ_{lt}	The average demand of customer $l \in D$ at period $t \in T$.
σ_{lt}^2	The variance of demand of customer $l \in IC$ at period $t \in T$.
Ξ	Lowest probability that each international customer's demand should be satisfied by at least one farmer.
ϑ	The minimum fraction of inter-hub transportation handled by ships for getting the economy advantageous of waterways.
pc_{kt}	Production cost of one unit product for farmer $k \in S$ at time $t \in T$.
c_{abp}	The distance among two nodes $a \in N$ and $b \in N$, regarding transportation mode $p \in P$
oc_p	Operation cost of one vehicle of transportation mode $p \in P$ for traveling one 3unit distance.
Cnd_l	Penalty cost of one unsatisfied demand of customer $l \in D$ at period $t \in T$
hc_{jk}	Holding cost of one unit inventory of farmer $k \in S$ at destination hub $j \in H$.
M	A big number.

Decision Variables

Z_{kj}	Binary variable which is one, if farmer $k \in S$ is allocated to hub $j \in H$.
Z_{lj}	Binary variable which is one, if customer $l \in D$ is allocated to hub $j \in H$.
C_{jq}^p	Binary variable which is one, if the capacity of $q \in Q$ is established for transportation mode $p \in P$ at hub $j \in H$.
$NV_{ij}^p(\omega)$	The number vehicles of transportation mode $p \in \{R, V\}$ at time $t \in T$ used for transporting products from hub i to hub $j \in H$ under scenario $\omega \in \Omega$.
$NRVS_{ki}^t(\omega)$	The number of trucks during period $t \in T$ used for transporting products from farmer $k \in S$ to hub $i \in H$ under scenario $\omega \in \Omega$.
$NRVD_{jl}^t(\omega)$	The number of trucks during period $t \in T$ used for transporting products from hub $j \in H$ to customer $l \in D$ under scenario $\omega \in \Omega$.
$NDV_{ki}^t(\omega)$	The number of trucks during period $t \in T$ used for transporting products from farmer $k \in S$ to customer $l \in D$ under scenario $\omega \in \Omega$.
$f_{ijkp}^t(\omega)$	The number of products produced by farmer $k \in S$ and transmitted by transportation mode $p \in \{R, V\}$ from origin hub $i \in H$ to destination hub $j \in H$ at time period $t \in T$ under scenario $\omega \in \Omega$.
$w_{kijl}^t(\omega)$	The number of products that farmer $k \in S$ send to customer $l \in D$, through hub origin $i \in H$ and hub destination $j \in H$ at time period $t \in T$ under scenario $\omega \in \Omega$.
A_{kijl}^t $w_{kijl}^t(\omega)$	The products sent from destination hub $j \in H$ toward customer $l \in D$ which are supplied by farmer $k \in S$ from origin hub $i \in H$ at period $t \in T$ under scenario $\omega \in \Omega$.
$O_{ki}^t(\omega)$	The total amount of products that farmer $k \in S$ send to hub $i \in H$ at time period t under scenario $\omega \in \Omega$.
$S_{ijkp}^t(\omega)$	The number of stocked products of farmer $k \in S$ at destination hub $j \in H$ transmitted by transportation mode $p \in P$ at period $t \in T$ from origin hub $i \in H$ under scenario $\omega \in \Omega$.
\hat{S}_{ijkp}^t $\hat{S}_{ijkp}^t(\omega)$	The number of pickup inventories of farmer $k \in S$ at destination hub $j \in H$ transmitted by transportation mode $p \in P$ at period $t \in T$ from origin hub $i \in H$ under scenario $\omega \in \Omega$.
I_{kijl}^t	The inventory level of farmer's products $k \in S$ transported from origin hub $i \in H$ and is stocked at destination hub $j \in H$ at period $t \in T$ to support customer $l \in D$ under scenario $\omega \in \Omega$.
$d_{kl}^t(\omega)$	The number of products directly transmitted from supplier $k \in S$ to customer $l \in D$ by truck at period $t \in T$ under scenario $\omega \in \Omega$.
nd_l	The slack variable that shows the amount of demand shortage for customer $l \in D$ during period $t \in T$ under scenario $\omega \in \Omega$.
pd_l	The surplus variable shows the amount of extra satisfied demand of customer $l \in D$ during period $t \in T$ under scenario $\omega \in \Omega$.
$x_{kl}^t(\omega)$	The binary variable is one, if farmer $k \in S$ decides to send its products to customer $l \in D$ by direct logistic policy at period $t \in T$ under scenario $\omega \in \Omega$.

3.3. Mathematical modeling

In this section, the model components including the network’s infrastructure, farmers supplying strategy and customers’ demand nature will be discussed. In the proposed poultry supply chain network, one great challenge is defining a suitable distribution system, where it ascertains the best locations of distribution centers (hub facilities), the interactions of farmers/customers with the located distribution centers, optimal storage policies of farmers’ production during pre-pandemic periods, and the optimal transportation modes for delivering of farmers’ products to customers. To cope with the above-mentioned issue, a multi-modal hub transportation system will be extended to the distribution system of the proposed poultry supply chain.

3.3.1. Multimodal hub transportation system under pandemic

Distributing commodities among a set of suppliers and customers in a large area, can be achieved either from establishing a direct path among each customer/supplier pair (Amin-Naseri et al., 2018) or using classical distribution systems that are adjusted only on one transportation type (Serper & Alumur, 2016). Hubs are facilities for collecting, sorting and dispatching flow that can not only reduce the number of direct paths and related costs, but also bring economy of scale through flow consolidation in inter hub routes. Hence, we propose a multi-modal hub transportation system consisting of track, ship and rail.

$H \in N$ is set of hub facilities. Suppose the binary variable Z_{kj} (Z_{ij}) is one, if farmer $k \in S$ (customer $l \in D$) is allocated to hub $j \in H$. Therefore, by assuming that each farmer/customer should be assigned to exactly one hub we have:

$$\sum_{j \in H} Z_{kj} = 1, \forall k \in S \tag{1}$$

$$\sum_{j \in H} Z_{lj} = 1, \forall l \in D \tag{2}$$

Constraints (3) and (4) demonstrate that as long as at node j the hub is not established, it cannot support customers or farmers.

$$Z_{kj} \leq Z_{jj}, \forall k \in S, j \in H \tag{3}$$

$$Z_{lj} \leq Z_{jj}, \forall l \in D, j \in H \tag{4}$$

While hub nodes support the whole transportation types, constraint (5) ensures that a single capacity needs to be selected for each transportation mode at each hub.

$$\sum_{q \in Q} G_{jq}^p \leq Z_{jj}, \forall j \in H, p \in P, \tag{5}$$

where G_{jq}^p is a binary variable that is one, if the capacity of q is established for transportation mode p at hub j .

Constraint (6) shows the number of hubs that should be located on the network.

$$\sum_{j \in H} Z_{jj} = NHF \tag{6}$$

Constraints (7) and (8) control the total number of vehicles that arrive at or depart from each hub node, respectively.

$$\sum_{j \in H, j \neq i} NV_{ijp}^t \leq \sum_q Vmax_q^p VPE_p^t G_{iq}^p, \forall i \in H, p \in \{R, V\}, t \in T \tag{7}$$

$$\sum_{i \in H, i \neq j} NV_{jip}^t \leq \sum_q Vmax_q^p VPE_p^t G_{jq}^p, \forall j \in N, p \in \{R, V\}, t \in T \tag{8}$$

The number of vehicles at each distribution path needs to be determined periodically. Hence, in equations (7) and (8), variable NV_{ijp}^t includes period index and is defined as the number of vehicles for transportation mode $p \in \{R, V\}$ at time t used for transporting farmers’ products from hub $i \in H$ to hub $j \in H$. $Vmax_q^p$ is the maximum available number of vehicles of transportation mode $p \in P$ with a capacity of q that can be accessed. Moreover, VPE_p^t is the accessibility level of transportation mode p at period t due to the pandemic severity. To balance the flow commodity among hub facilities we have:

$$\sum_{j \in H, j \neq i} \sum_{p \in P} f_{ijkp}^t - \sum_{j \in H, j \neq i} \sum_{p \in P} f_{jikp}^t = O_{ki}^t - \sum_{l \in D} w_{kil}^t Z_{li}, i \in H, k \in S \tag{9}$$

where f_{ijkp}^t is the number of products that are produced by farmer $k \in S$ and is transmitted by transportation mode $p \in \{R, V\}$ from origin hub $i \in H$ to destination hub $j \in H$ at period $t \in T$. Variable w_{kil}^t is the number of products that farmer k send to customer l at period t , and variable O_{ki}^t expresses the total amount of products that farmer k send to hub i at period t . The term $w_{kil}^t Z_{li}$ in equations (8) makes the model non-linear. To linearize this equation, we propose the below procedure.

In equation (9), $w_{kil}^t Z_{li}$ calculates the number of products that farmer k send to customer l at period t , through only one hub i which

means both farmer k and customer l are assigned to hub i . Therefore, $w_{kil}^t Z_{li}$ can be substituted by variable w_{kil}^t according to equations (10)-(13).

$$w_{kil}^t \geq w_{kil}^t - M.(2 - Z_{ki} - Z_{li}), \forall k \in S, \forall l \in D, i \in H, t \in T \tag{10}$$

$$w_{kil}^t \leq w_{kil}^t, \forall k \in S, \forall l \in D, i \in H, t \in T \tag{11}$$

$$w_{kil}^t \leq M.Z_{ki}, \forall k \in S, \forall l \in D, i \in H, t \in T \tag{12}$$

$$w_{kil}^t \leq M.Z_{li}, \forall k \in S, \forall l \in D, i \in H, t \in T \tag{13}$$

Also the variable O_{ki}^t can be obtained by equation (14):

$$O_{ki}^t = \sum_{l \in D} \sum_{j \in H} w_{kijl}^t, \forall k \in S, i \in H, t \in T \tag{14}$$

Now by replacing variable w_{kil}^t in equation (9), the linearized flow balance equation is introduced according to equation (15).

$$\sum_{j \in H, j \neq i} \sum_{p \in P} f_{ijkp}^t - \sum_{j \in H, j \neq i} \sum_{p \in P} f_{jikp}^t = O_{ki}^t - \sum_{l \in D} w_{kil}^t, i \in H, k \in S \tag{15}$$

To control the negative effect of pandemic, a farmer will decide to stock or remove a fraction of products at hub facilities. As destination hubs are closer to customer zones, selecting them as a warehouse is always superior to origin hubs. Therefore, the output flow from destination hub j toward customer l that is supplied by farmer k from origin hub i at period t (\hat{w}_{kijl}^t) can be concluded as follows:

$$\hat{w}_{kijl}^1 = w_{kijl}^1 ACPE_l^1 - S_{kijl}^1, k \in S, i, j \in H, l \in D \tag{16}$$

$$\hat{w}_{kijl}^t = w_{kijl}^t ACPE_l^t - S_{kijl}^t + \hat{S}_{kijl}^t, k \in S, i, j \in H, l \in D, t \in T \setminus \{1, |T|\} \tag{17}$$

$$\hat{w}_{kijl}^T = w_{kijl}^T ACPE_l^T + \hat{S}_{kijl}^T, k \in S, i, j \in H, l \in D \tag{18}$$

According to equation (16), a farmer only can stock products during the first period (S_{kijl}^1), since there is no initial inventory of products at destination hubs. Based on equation (18), in the last period, farmers cannot stock their products ($S_{kijl}^T = 0$), since there are no farther periods. In the middle periods ($t \in T \setminus \{1, |T|\}$) either stocking (S_{kijl}^t) or removing (\hat{S}_{kijl}^t) the inventories is permitted (equation (17)). In equations (16) to (18), $ACPE_l^t \in [0, 1]$ is a parameter which shows the accessibility level to customer l with respect to pandemic severity during period t . The higher value of $ACPE_l^t$, the more accessibility to customer l .

Now the value of inventory production of farmers k that is transported from origin hub i and is stocked at destination hub j at period t to support customer l (I_{kijl}^t) can be obtained by equations (19)-(21).

$$I_{kijl}^1 = I_{kijl}^0 + S_{kijl}^1, k \in S, i, j \in H, l \in D \tag{19}$$

$$I_{kijl}^t = I_{kijl}^{t-1} + S_{kijl}^t - \hat{S}_{kijl}^t, k \in S, i, j \in H, l \in D, t \in \{2, \dots, |T| - 1\} \tag{20}$$

$$I_{kijl}^{|T|} = I_{kijl}^{|T|-1} - \hat{S}_{kijl}^{|T|}, k \in S, i, j \in H, l \in D \tag{21}$$

Equation (21) computes the number of vehicles of each transportation mode for inter-hub routes under Pandemic condition.

$$\sum_{k \in N} f_{ijkp}^t \leq cap_{ijp}^t VPE_p^t NV_{ijp}^t, \forall i, j \in H, i \neq j, p \in \{R, V\}, t \in T, \tag{22}$$

where cap_{ijp}^t is the maximum capacity of transportation mode p at period t in path $i \rightarrow j$.

3.3.2. Farmers' supplying strategy and customers' demand nature

The poultry supply chain network consists of S farmers. For the farmer k , the total production at each period t depends on the number of poultry home (\mathcal{L}_{ik}) and the production rate of each poultry home ($\check{I}_{ik}(\omega)$) that is affected by COVID-19. $\check{I}_{ik}(\omega)$ shows the production rate of each poultry home at period t under scenario $\omega \in \Omega$. Under scenario $\omega \in \Omega$ the amount of production for farmer k at period t ($tp_{kt}(\omega)$) can be calculated as follows:

$$tp_{ik}(\omega) = \mathcal{L}_{ik} \check{I}_{ik}(\omega) MPE^t, \forall k \in S, t \in T \tag{23}$$

where MPE^t is the percentage of production rate that can be accessed regardless of pandemic severity during time t . Under scenario $\omega \in \Omega$, farmer k at period t should decide the amount of products that need to supply to customer l through hub origin i and hub destination j ($w_{kijl}^t(\omega)$), which depends on the customers' demands. The domestic customer $l \in DC$ has a constant demand rate μ_{lt} , $\forall l \in DC$ at period t ; while the international customer $l \in IC$ has stochastic demand pattern ($demand_{lt}$) that follows normal distribution function with mean μ_{lt} , $\forall l \in IC$ and variance σ_{lt}^2 , $\forall l \in IC$ at each period $t \in T$. To model the customers' stochastic demand, the chance constraint procedure is applied. According to the equation (24), under scenario $\omega \in \Omega$, to avoid penalty cost on poultry supply chain, the demand of international customer $\forall l \in IC$ should be satisfied by at least one farmer with the probability of at least Ξ :

$$\Pr\left(\sum_{k \in S} \sum_{i \in H} \sum_{j \in H} w_{kijl}^t(\omega) \geq demand_{lt}\right) \geq \Xi, \forall l \in IC, t \in T \tag{24}$$

With $demand_{lt} \sim N(\mu_{lt}, \sigma_{lt}^2)$, the chance constraint of equation (25) can be expressed as follows:

$$\sum_{k \in S} \sum_{i \in H} \sum_{j \in H} w_{kijl}^t(\omega) \geq \mu_{lt} + \mathcal{Z}_{\Xi} \sigma_{lt}, \forall l \in IC, t \in T \tag{25}$$

where \mathcal{Z}_{Ξ} is the \mathcal{Z} -value regarding the $100\Xi^{th}$ percentile from the standard normal distribution. During the pandemic (especially severe condition), different parts of the supply chain are affected; thus, meeting constraint (25) is practically impossible. To overcome this shortcoming, we relax constraint (24) by imposing a penalty cost for each unit demand shortage relative to the minimum required confidence to meet customers' demand. In equation (26), $nd_{lt}(\omega)$ and $pd_{lt}(\omega)$ are slack and surplus variables regarding the right side of the equation. It should be noted that slack variable $nd_{lt}(\omega)$ shows the amount of demand shortage for customer $\forall l \in D$ during period $t \in T$ under scenario $\omega \in \Omega$. Hence, $nd_{lt}(\omega)$ imposes a penalty cost of $Cnd_{lt}nd_{lt}(\omega)$ to the poultry supply chain, where Cnd_{lt} shows the unit penalty cost that should be paid to customer $\forall l \in D$ during period $t \in T$.

$$\sum_{k \in S} \sum_{i \in H} \sum_{j \in H} \hat{w}_{kijl}^t(\omega) + nd_{lt}(\omega) - pd_{lt}(\omega) = \mu_{lt} + \mathcal{Z}_{\Xi} \sigma_{lt}, \forall l \in IC, t \in T \tag{26}$$

3.3.3. Model 1: Poultry supply chain Model under pandemic without direct path among farmers and customers

Since the farmers' production policies are affected by risk of diseases, the model's variables are categorized in two categories: strategic variables (\mathcal{X}) and uncertain variables (ω). The strategic variables determine the hub facility locations, farmer/customer allocation to them and transportation capacity installation for different conveyers $x = \{Z_{kj}, Z_{lj}, Z_{ji}, G_{jq}^p\}$. The uncertain variables are associated with flow distribution policies and should be considered under the scenario $\omega \in \Omega$ as $f_{ijkp}^t(\omega) \geq 0, O_{ki}^t(\omega) \geq 0, S_{kijl}^t(\omega) \geq 0, I_{ijkp}^t(\omega) \geq 0, w_{kijl}^t(\omega) \geq 0, NV_{ijp}^t(\omega) \geq 0, NRVS_{ki}^t(\omega) \geq 0$ and $NRVD_{jl}^t(\omega) \geq 0$. Hence, we organize the model's formulation in two sub-models. The first sub-model is **design** and the second sub-model is **operation**. Pr_{ω} is the probability of scenario $\omega \in \Omega$ for poultry diseases risk. $Pr_{\omega} \beta(x, \omega)$ is the expected value of the second sub-model's objective function. Therefore, the mathematical formulation of Model 1 can be formulated as follows:

$$\min Obj_{Model\ 1} = \sum_{p \in P \setminus RV} \sum_{j \in H} \sum_{q \in Q} cc_{jq}^p G_{jq}^p + \sum_{\omega \in \Omega} Pr_{\omega} \beta(x, \omega)$$

Subject to:
(1)~(6)

$$Z_{ij} \in \{0, 1\}, G_{jq}^p \in \{0, 1\}, \forall j \in H, i \in N, p \in P, q \in Q \tag{27}$$

The objective function aims at minimizing the total costs of establishing transportation at hub facilities and the expected cost of the second sub-model. In the first term of objective function, parameter cc_{jq}^p is the cost of establishing capacity q of transportation mode p at hub j . When the hub facilities are located, in the second sub-model, the production costs, the flow distribution policy including transportation costs from farmers to hub nodes, inter hub flow distribution costs, transportation costs from hub nodes to customers and holding inventory costs are minimized. To address the poultry diseases risk, a fixed number of scenarios $|\Omega|$ are randomly generated and applied in the model. Thus, the mathematical formulation of the second sub-model can be presented as follows:

$$\min \sum_{\omega \in \Omega} Pr_{\omega} \beta(x, \omega) \tag{28}$$

where, for $\omega \in \Omega$,

$$\beta(x, \omega) =$$

$$\sum_{k \in S} \sum_{t \in T} p_{kt} tp_{kt}(\omega) + \tag{28.1}$$

$$\sum_{k \in S} \sum_{i \in H} \sum_{t \in T} c_{kiRV} NRVS_{ki}^t(\omega) oc_{RV} + \tag{28.2}$$

$$\sum_{l \in D} \sum_{j \in H} \sum_{t \in T} c_{jIRV} NRVD_{jl}^t(\omega) oc_{RV} + \tag{28.3}$$

$$\sum_{i \in H} \sum_{j \in H} \sum_{p \in P \setminus RV} \sum_{t \in T} c_{ijp} NV_{ijp}^t(\omega) oc_p + \tag{28.4}$$

$$\sum_{l \in D} \sum_{t \in T} Cnd_{lt} nd_{lt}(\omega) + \tag{28.5}$$

$$\sum_{k \in S} \sum_{i \in H} \sum_{j \in H} \sum_{l \in D} \sum_{t \in T} hc_{it} I_{kijl}^t(\omega) \tag{28.6}$$

Subject to:

(23), (26)

$$\sum_{i \in H} O_{ki}^t(\omega) \leq tp_{kt}(\omega), \forall k \in S, t \in T \tag{29}$$

$$\sum_{k \in S} \sum_{i \in H} \sum_{j \in H} \hat{w}_{kijl}^t(\omega) + nd_{lt}(\omega) - pd_{lt}(\omega) = \mu_{lt}, \forall l \in DC, t \in T \tag{30}$$

$$\sum_{j \in H, j \neq i} NV_{ijp}^t(\omega) \leq \sum_{q \in Q} Vmax_q^p VPE_p^t G_{iq}^p, \forall i \in H, p \in \{R, V\}, t \in T \tag{31}$$

$$\sum_{i \in H, i \neq j} NV_{ijp}^t(\omega) \leq \sum_{q \in Q} Vmax_q^p VPE_p^t G_{jq}^p, \forall j \in H, p \in \{R, V\}, t \in T \tag{32}$$

$$O_{ki}^t(\omega) = \sum_{l \in D} \sum_{j \in H} w_{kijl}^t(\omega), \forall k \in S, i \in H, t \in T \tag{33}$$

$$w_{kijl}^t(\omega) \leq M.Z_{ki}, \forall k \in S, \forall l \in D, i \in H, t \in T \tag{34}$$

$$w_{kijl}^t(\omega) \leq M.Z_{li}, \forall k \in S, \forall l \in D, i \in H, t \in T \tag{35}$$

$$\sum_{j \in H, j \neq i} \sum_{p \in P} f_{ijkp}^t(\omega) - \sum_{j \in H, j \neq i} \sum_{p \in P} f_{jikp}^t(\omega) = O_{ki}^t(\omega) - \sum_{l \in D} w_{kijl}^t(\omega), i \in H, k \in S \tag{36}$$

$$\hat{w}_{kijl}^1(\omega) = w_{kijl}^1(\omega) ACPE_l^1 - S_{kijl}^1(\omega), k \in S, i, j \in H, l \in D \tag{37}$$

$$\hat{w}_{kijl}^t(\omega) = w_{kijl}^t(\omega) ACPE_l^t - S_{kijl}^t(\omega) + \hat{S}_{kijl}^t(\omega), k \in S, i, j \in H, l \in D, t \in T \setminus \{1, |T|\} \tag{38}$$

$$\hat{w}_{kijl}^T(\omega) = w_{kijl}^T(\omega) ACPE_l^T + \hat{S}_{kijl}^T(\omega), k \in S, i, j \in H, l \in D \tag{39}$$

$$I_{kijl}^1(\omega) = I_{kijl}^0(\omega) + S_{kijl}^1(\omega), k \in S, i, j \in H, l \in D \tag{40}$$

$$I_{kijl}^t(\omega) = I_{kijl}^{t-1}(\omega) + S_{kijl}^t(\omega) - \hat{S}_{kijl}^t(\omega), k \in S, i, j \in H, l \in D, t \in \{2, \dots, |T| - 1\} \tag{41}$$

$$I_{kijl}^{|T|}(\omega) = I_{kijl}^{|T|-1}(\omega) - \hat{S}_{kijl}^{|T|}(\omega), k \in S, i, j \in H, l \in D \tag{42}$$

$$\sum_{k \in S} f_{ijkp}^t(\omega) \leq cap_{ijp}^t NV_{ijp}^t(\omega) VPE_p^t, \forall i, j \in H, i \neq j, p \in \{R, V\}, t \in T \tag{43}$$

$$O_{ki}^t(\omega) \leq cap_{kiRV}^t NRVS_{ki}^t(\omega) VPE_{RV}^t, \forall k \in S, i \in H, t \in T \tag{44}$$

$$\sum_{k \in S} \sum_{i \in H} \hat{w}_{kij}^t(\omega) \leq cap_{jirv}^t NRVD_{ji}^t(\omega) VPE_{RV}^t, \forall k \in S, j \in H, t \in T \tag{45}$$

$$\sum_{k \in S} \sum_{i \in H} NRVS_{ki}^t(\omega) + \sum_{l \in D} \sum_{j \in H} NRVD_{jl}^t(\omega) \leq \sum_{q \in Q} vmax_q^{RV} VPE_{RV}^t, t \in T \tag{46}$$

$$\sum_{k \in N} \sum_{i \in H} \sum_{j \in H} \sum_{p \in V} f_{ijkp}^t(\omega) \geq \bar{a} \sum_{k \in N} \sum_{i \in H} \sum_{j \in H} \sum_{p \in P \setminus RV} f_{ijkp}^t(\omega), \quad \forall t \in T \tag{47}$$

$$f_{ijkp}^t(\omega) \geq 0, O_{ki}^t(\omega) \geq 0, S_{kij}^t(\omega) \geq 0, \hat{S}_{kijl}^t(\omega) \geq 0, I_{ijkp}^t(\omega) \geq 0, w_{kijl}^t(\omega) \geq 0$$

$$NV_{ijp}^t(\omega) \geq 0, NRVS_{ki}^t(\omega), NRVD_{jl}^t(\omega) integer \forall k \in S, l \in D, i \in H, j \in H, p \in P \tag{48}$$

According to the objective function, the equation (28.1) counts the total production costs of whole farmers. Equations (28.2) and (28.3) represent the total costs of trucks for transportation products from farmers to origin hub routes and destination hubs to customers routes, respectively. Equation (28.4) shows the total conveyor costs for inter-hub routes. Equations (28.5) shows the total penalty costs of unsatisfied customers' demands. Equation (28.6) shows the total inventory holding costs of farmers' production at destination hub nodes during different periods. Constraints (23) and (29) show the capacity and the amount of production at each period for each farmer. Constraints (26) and (30) guarantee that international and domestic customers' demands are met, respectively. Constraints (31) and (32) restrict the total number of conveyor units including ship and train for inter hub routes regarding pandemic effect. Constraints (33) shows the number of farmers' productions. Constraints (34) to (36) calculates the flow balance equations of the distribution network. Constraints (37) to (39) determine the output flow of destination hubs under inventory policy and pandemic effect for the first period, median periods and the last period, respectively. Constraints (40) to (42) compute the inventory level of each farmer at each destination hub in each time period. Constraint (43) calculates the total number of ships or trains in inter-hub routes regarding pandemic effect. By considering pandemic effect and for each time period and under each scenario $\omega \in \Omega$, constraint (44) and (45) determine the total number of trucks for farmer-origin hub routes ($NRVS_{ki}^t(\omega)$) and total number of trucks for destination hub-customers routes ($NRVD_{jl}^t(\omega)$), respectively. Constraint (46) restricts the number of trucks in non-hub to hub routes. Constraint (47) guarantees that a specific percentage (\bar{a}) amount of flow transmission should be handled by ships for using the potential economy advantageous of water-way transportation. Constraint (48) enforces the binary and non-negativity conditions for the variables.

3.3.4. Model 2: The poultry supply chain model under pandemic with direct paths among farmers and customers

In the model 1, to satisfy the customers' demands, farmers cannot send their products directly to the customers and must use multi-modal logistic policy. This strategy may decrease the distribution system efficacy, especially when customers are located near the farmers. To cope with this issue, we further develop model 2 under the condition that there is a possibility of sending products from farmers to customers through direct routes.

Let $df_{kl}^t(\omega)$ define the amount of products directly transmit from farmer $k \in S$ to customer $l \in D$ using truck at period t under scenario $\omega \in \Omega$. Thus, the farmers production equation (29) needs to be revised based on this new variable as follows:

$$\sum_{i \in H} O_{ki}^t(\omega) + \sum_{l \in D} df_{kl}^t(\omega) \leq tp_{ki}(\omega), \forall k \in S, t \in T \tag{48}$$

To control the transportation costs, farmer $k \in S$ must choose only one of the direct ($df_{kl}^t(\omega)$) or indirect ways ($\hat{w}_{kijl}^t(\omega)$) for transporting its products toward customer $l \in D$. Therefore, in period t , the value of $\hat{w}_{kijl}^t(\omega) \times df_{kl}^t(\omega)$ must be zero. Accordingly, let $x_{kl}^t(\omega)$ define a binary variable which is one, if farmer $k \in S$ decides to send its products to customer $l \in D$ by a direct path at period t and zero otherwise.

$$df_{kl}^t(\omega) \leq Mx_{kl}^t(\omega), \forall k \in S, t \in T, l \in D \tag{49}$$

$$\hat{w}_{kijl}^t(\omega) \leq M(1 - x_{kl}^t(\omega)), \forall k \in S, t \in T, l \in D, i \in H, j \in H \tag{50}$$

When $x_{kl}^t(\omega) = 1$, the right side of equation (49) will be a big number and permits the variable $df_{kl}^t(\omega)$ to get value. On the contrary, the right side of equation (50) will be zero which means the variable $\hat{w}_{kijl}^t(\omega)$ must be zero. For the situation that $x_{kl}^t(\omega) = 0$, the value of $df_{kl}^t(\omega)$ is zero and variable $\hat{w}_{kijl}^t(\omega)$ can get value. By introducing two types of supplying strategy, the chance constraint equations (26) and (30) of international and domestic customers' demand should be revised as follows:

$$\sum_{k \in S} \sum_{i \in H} \sum_{j \in H} \hat{w}_{kijl}^t(\omega) + \sum_{k \in S} df_{kl}^t(\omega) + nd_l(\omega) - pd_l(\omega) = \mu_l + \mathcal{Z} \pm \sigma_l, \forall l \in IC, t \in T \tag{51}$$

$$\sum_{k \in S} \sum_{i \in H} \sum_{j \in H} \hat{w}_{kij}^t(\omega) + \sum_{k \in S} df_{kl}^t(\omega) + nd_l(\omega) - pd_l(\omega) = \mu_l, \forall l \in DC, t \in T \tag{52}$$

Based on equations (51) and (52), it can be seen that the first part of Model 2 is the same as the first part of Model 1. The second-sub model of Model 2 is as follows:

$$\min \sum_{\omega \in \Omega} Pr_{\omega} \beta(x, \omega) \tag{53}$$

where, for $\omega \in \Omega$,

$$\beta(x, \omega) =$$

$$\sum_{i \in S} \sum_{t \in T} pc_{it} tp_{it}(\omega) + \tag{53.1}$$

$$\sum_{k \in S} \sum_{i \in H} \sum_{t \in T} c_{kiRV} NRVS_{ki}^t(\omega) oc_{RV} + \tag{53.2}$$

$$\sum_{l \in D} \sum_{j \in H} \sum_{t \in T} c_{jIRV} NRVD_{jl}^t(\omega) oc_{RV} + \tag{53.3}$$

$$\sum_{i \in H} \sum_{j \in H} \sum_{p \in P \setminus RV} \sum_{t \in T} c_{kip} NV_{ip}^t(\omega) oc_p + \tag{53.4}$$

$$\sum_{l \in D} \sum_{t \in T} Cnd_l nd_l(\omega) + \tag{53.5}$$

$$\sum_{k \in S} \sum_{i \in H} \sum_{j \in H} \sum_{l \in D} \sum_{t \in T} hc_{it} I_{kijl}^t(\omega) + \tag{53.6}$$

$$\sum_{k \in S} \sum_{l \in D} \sum_{t \in T} c_{klRV} NDV_{kl}^t(\omega) oc_{RV} \tag{53.7}$$

Subject to:

(23), (31)–(45)

$$\sum_{i \in H} O_{ki}(\omega) + \sum_{l \in D} df_{kl}^t(\omega) \leq tp_{ki}(\omega), \forall k \in S, t \in T \tag{48}$$

$$df_{kl}^t(\omega) \leq Mx_{kl}^t(\omega), \forall k \in S, t \in T, l \in D \tag{49}$$

$$\hat{w}_{kijl}^t(\omega) \leq M(1 - x_{kl}^t(\omega)), \forall k \in S, t \in T, l \in D, i \in H, j \in H \tag{50}$$

$$\sum_{k \in S} \sum_{i \in H} \sum_{j \in H} \hat{w}_{kijl}^t(\omega) + \sum_{l \in D} df_{kl}^t(\omega) + nd_l(\omega) - pd_l(\omega) = \mu_l + \mathcal{Z}_{\pm} \sigma_l, \forall l \in IC, t \in T \tag{51}$$

$$\sum_{k \in S} \sum_{i \in H} \sum_{j \in H} \hat{w}_{kijl}^t(\omega) + \sum_{l \in D} df_{kl}^t(\omega) + nd_l(\omega) - pd_l(\omega) = \mu_l, \forall l \in DC, t \in T \tag{52}$$

$$df_{kl}^t(\omega) \leq cap_{klRV}^t NDV_{kl}^t(\omega) VPE_{RV}^t, \forall k \in S, l \in D, t \in T \tag{54}$$

$$\sum_{k \in S} \sum_{i \in H} NRVS_{ki}^t(\omega) + \sum_{l \in D} \sum_{j \in H} NRVD_{jl}^t(\omega) + \sum_{k \in S} \sum_{l \in D} NDV_{kl}^t(\omega) \leq \sum_{q \in Q} Vmax_q^{RV} VPE_{RV}^t, t \in T \tag{55}$$

$$x_{kl}^t(\omega) \in \{0, 1\}, \forall k \in S, l \in D, t \in T \tag{56}$$

The objective function aims at minimizing the total production cost, transportation costs in direct and indirect routes from farmers to customers, total inventory costs and total penalty costs of unsatisfied customers' demands. In this regard, equations (53.1) to (53.6) have the same definitions to equations (28.1) to (28.6) and equation (53.7) calculates the total transportation costs of trucks in direct routes from farmers to customers. According to constraint (48) the total amount of direct and indirect flow distribution for each farmer should not exceed its production capacity. Constraints (49) and (50) guarantee that to support a customer each farmer should select either direct or indirect logistic policy. Constraints (51) and (52) ensure that in each period international and domestic customers'

demands should be satisfied. Constraint (54) counts the total number of trucks that should be employed in direct logistic routes regarding pandemic effect. Constraint (55) restricts the number of trucks in whole the poultry supply chain in both the direct and indirect logistic policies. Constraint (56) shows the new binary variable $x_{kl}^c(\omega)$ that has been introduced in this section.

In addition to consider the infrastructure required for the agriculture supply chain, the develop model also takes into account the specific items of poultry supply chain, including: 1) modeling the impacts of uncertainties related to seasonal variations and the COVID-19 pandemic on farmers' production rate; 2) considering to store farmers' poultry products at hub facilities during pre and early pandemic outbreak, to respond customers' demand during the pandemic period; 3) modeling the negative effects of COVID-19 pandemic regarding its severity in different periods on different segments of the poultry supply chain including farmers, distribution system and customer areas; and 4) developing a multi-echelon transportation system under different logistics policies to improve the performance of the distribution network during pandemic period at with least cost.

To estimate the order complexity of Model 1 and Model 2, we apply an approximation procedure. Considering the fact that $S \in N, D \in N, H \in N$, we use $|N|$ as an upper bound for S, D and H sets. Therefore, the upper bound of the number of constraints for Model 1 will be $2|N|^4|T| + 2|N|^3|T| + 6|N|^2|T| + 8|N||T| + 2|N|^4 + 2|N|^2 + 5|N| + 2|T| + 1$, and the upper bound for the number of variables for Model 1 will be $5|N|^4|T| + |N|^3|T| + 3|N|^2|T|$ with the rest $|N|^3|T| + 2|N|^2|T|$ variables are integer. The order complexity for Model 1 is approximately $O(|N|^4|T|)$. Similarly, the upper bound for the number of constraints for Model 2 is approximately $3|N|^4|T| + 2|N|^3|T| + 6|N|^2|T| + 8|N||T| + 4|N|^4 + 2|N|^2 + 5|N| + 3|T| + 1$, and the upper bound of the number of variables for Model 2 can be approximated as $5|N|^4|T| + |N|^3|T| + 4|N|^2|T|$, the rest $|N|^3|T| + 3|N|^2|T|$ variables are integer. Hence, $O(|N|^4|T|)$ is the order complexity of Model 2. The approximated order complexities of Model 1 and Model 2 indicate that obtaining exact solutions even for small problem-size will be challenging. To overcome this shortcoming, in section 4, an efficient solution procedure will be introduced.

4. Solution approach

To obtain solutions for the proposed poultry food supply chain model, a hybrid algorithm based on Branch-and-Cut (B&C) and Dynamic Programming (DP), that henceforth is called BBDP, is developed. The B&C part of the proposed solution approach includes three steps: step1) hub facilities selection, step2) farmers/customers allocation to the selected hubs, and step 3) determining the amount of flow that should be sent from each farmer to each customer at each period. For improving the performance of the B&C, we employ series of inequalities, lower bounds estimation and two variable neighborhood search algorithms as the upper bound estimators. The DP part of the BBDP solution procedure aims at determining the amount of stock/pick up inventory values for each farmer at each destination hub in each period, as step 4 of BBDP model. In the following each step of BBDP is introduced in detail.

4.1. Step 1: Hub selection

The B&C algorithm determines the location of hub facilities among set H . For this purpose, a Breadth-First Search (BFS) structure is applied. The first depth of the search tree includes H branches. For node i at the second depth, $|H| - i$ sub-branches can be imagined. This is due to the fact that firstly each node can be selected as one hub facility and secondly the algorithm needs to determine only a combination set of hub facilities. Therefore, at depth $d \mid d \leq p$, the algorithm opens at most $\binom{|H|}{d}$ branches. Fig. 2 shows the BFS tree search of step1.

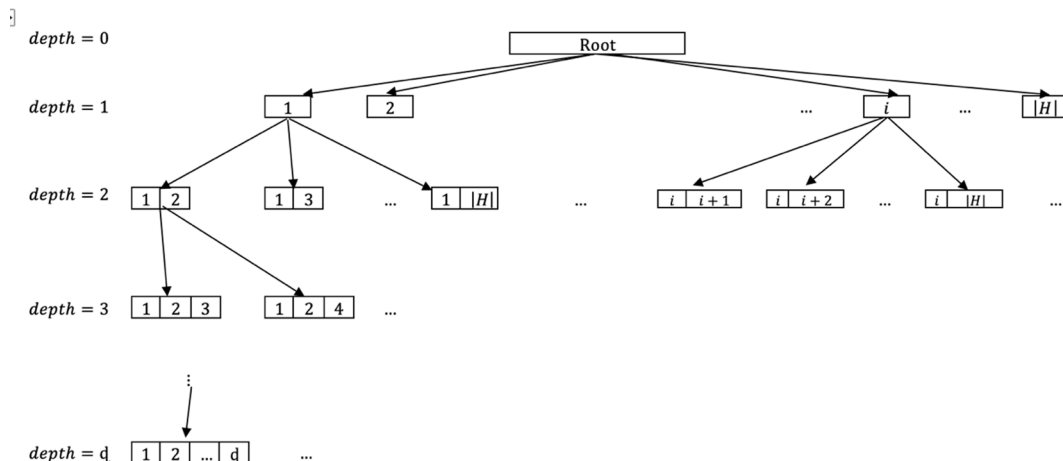


Fig. 2. BFS tree of B&C Step 1.

4.2. Step 2: Farmers/Customers allocation

This step aims at allocating non-hub nodes (farmers/customers) to the selected hubs. For this purpose, for every branch of step one, as one possible hub facilities structure, the B&C algorithm determines the allocation structure of farmers/customers to the current hubs of that branch. Therefore, search tree follows BFS policy under which at most $|S| + |D|$ depths can be opened. At this step, the algorithm starts with first farmer's node and opens p branches as different possible allocation structure for the farmer. According to this policy for farmer/customer that is at depth $\{d \mid d \leq |S| + |D|\}$, at most p^d branches can be imagined. The lower bound of this step is calculated as follows.

4.2.1. Lower bound estimation

At depth $\{d \mid d \leq |S| + |D|\}$, consider branch $\{f_{j_1}, f_{j_2}, \dots, f_{j_d}, 0, 0, \dots, 0\}$, where $\hat{E}_{S_i} \in H$ shows the hub facility which supports the non-hub node i ($i \in \{S, D\}$) (and zero values show the non-assigned nodes). The lower bound of transportation costs for this branch (LB_d) can be calculated according to the sub-problem A.

Sub-problem A

$$\begin{aligned}
 LB_d = \min & \sum_{k=1}^d \sum_{l \in \{|S|+1, \dots, d\}} c_{k\hat{f}_k} + c_{\hat{f}_k\hat{f}_l} + c_{\hat{f}_l l} \\
 & + \sum_{k=1}^d \sum_{l \in \{d+1, \dots, |S|+|D|\}} \sum_{i \in H} c_{k\hat{f}_k} + (c_{\hat{f}_k i} + c_{li}) \chi_{li} \\
 & + \sum_{k=d+1}^{|S|+|D|} \sum_{l \in \{|S|+1, \dots, d\}} \sum_{i \in H} (c_{ki} + c_{k\hat{f}_l}) \chi_{ki} + c_{\hat{f}_l l} \\
 & + \sum_{k=d+1}^{|S|+|D|} \sum_{l \in \{d+1, \dots, |S|+|D|\}} \sum_{i \in H} \sum_{j \in H} (c_{ki} + c_{ij} + c_{lj}) \chi_{kijl}
 \end{aligned} \tag{57}$$

Subject to:

$$\sum_{i \in H} \chi_{ki} \geq 1, \quad \forall k \in \{d+1, \dots, |S| + |D|\} \tag{58}$$

$$(\chi_{ki} + \chi_{lj} - 1) \leq \chi_{kijl}, \quad \forall k, l \in \{d+1, \dots, |S| + |D|\}, \forall i, j \in H \tag{59}$$

$$\chi_{ki} \in \{0, 1\}, \chi_{kijl} \in \{0, 1\}, \forall k \in S, l \in D, i, j \in H \tag{60}$$

According to equation (57), the first term shows the transportation costs among farmers and customers whom are assigned to the current hub facilities. Second term calculates the total amount of transportation cost from assigned farmers to those customers that are not assigned to any hub. Third term attains the total transportation cost from non-assigned farmers to assigned customers and fourth term shows the total transportation cost among non-assigned farmers to non-assigned customers. Constraint (58) relaxed the single allocation assumption of the original model. Therefore, every farmer for sending its products to a given customer, have access to different origin/destination hubs. Constraint (60) ensures the feasibility of path $k \rightarrow i \rightarrow j \rightarrow l$, when farmer k and customer l are assigned to hub origin i and hub destination j , respectively. To calculate second to fourth terms of objective function, the *sub-problem A* need to determine the allocation of non-hub nodes that are not assigned. In this regard, for farmer k , suppose the origin hub is specified as \hat{E}_{S_k} , so $c_{k\hat{E}_{S_k}} + \min_{i \in H} \{c_{\hat{E}_{S_k} i} + c_{il}\}$ is the lowest transportation cost path among farmer k and customer l . Let, $c_{\hat{E}_{S_k} il}^{min} = \min_{i \in H} \{c_{\hat{E}_{S_k} i} + c_{il}\}$, now the second term of objective function can be rewritten as follows $\sum_{k=1}^d \sum_{l \in \{d+1, \dots, |S|+|D|\}} \sum_{i \in H} c_{k\hat{f}_k} + c_{\hat{f}_k il}^{min}$. For customer l , suppose the destination hub is specified as \hat{E}_{S_l} , so $\min_{i \in H} \{c_{ki} + c_{k\hat{E}_{S_l}}\} + c_{\hat{E}_{S_l} l}$ is the lowest transportation cost path among farmer k and customer l . Let, $c_{ki\hat{E}_{S_l}}^{min} = \min_{i \in H} \{c_{ki} + c_{k\hat{E}_{S_l}}\}$, now the third term of objective function can be rewritten as follows $\sum_{k=d+1}^{|S|+|D|} \sum_{l \in \{|S|+1, \dots, d\}} \sum_{i \in H} c_{ki\hat{f}_k}^{min} + c_{\hat{f}_l l}$. Consider the case under which both farmer k and customer l are not assigned to the hubs' set, at this condition by introducing $c_{kijl}^{min} = \min_{i, j \in H} \{c_{ki} + c_{ij} + c_{lj}\}$, the fourth term can be rewritten as follows $\sum_{k=d+1}^{|S|+|D|} \sum_{l \in \{d+1, \dots, |S|+|D|\}} \sum_{i \in H} \sum_{j \in H} c_{kijl}^{min}$. Hence, the lower bound of branch $\{f_{j_1}, f_{j_2}, \dots, f_{j_d}, 0, 0, \dots, 0\}$ is calculated by equation (61)

$$\begin{aligned}
 LB_{\{f_{11}, f_{12}, \dots, f_{1d}, 0, 0, \dots, 0\}} &= \sum_{k=1}^d \sum_{l \in \{|S|+1, \dots, d\}} c_{k\hat{f}_k} + c_{\hat{f}_k \hat{f}_l} + c_{\hat{f}_l l} \\
 &+ \sum_{k=1}^d \sum_{l \in \{d+1, \dots, |S|+|D|\}} \sum_{i \in H} c_{k\hat{f}_k} + c_{\hat{f}_k i}^{min} \\
 &+ \sum_{k=d+1}^{|S|+|D|} \sum_{l \in \{|S|+1, \dots, d\}} \sum_{i \in H} c_{ki\hat{f}_k}^{min} + c_{\hat{f}_l l} \\
 &+ \sum_{k=d+1}^{|S|+|D|} \sum_{l \in \{d+1, \dots, |S|+|D|\}} \sum_{i \in H} \sum_{j \in H} c_{kijl}^{min}
 \end{aligned} \tag{61}$$

4.2.2. Upper bound estimation (VNS algorithm)

In this section we will expand a variable neighborhood search (VNS) algorithm to obtain a tight upper bound solution for hub location and farmer/customer allocation to the selected hubs. VNS has been widely applied to solve optimization problems (Duan et al., 2021). The pseudo-code of the VNS algorithm of the can be seen in Fig. 3.

4.3. Step 3: Determining the amount sent from each farmer to each customer

At this step the B&C algorithm needs to specify the distribution policy of farmers to support the customers. For this purpose, for each branch of step 2, B&C applies BFS policy to explore different possible branches of step 3. Each branch of step three can be imagined as a super matrix of $(|S| \times |D| \times |T|)$, where the element (k, l, t) of this matrix shows the number of products that farmer $k \in S$ sends to customer $l \in D$ at time period $t \in T$. For improving the performance of the algorithm, we utilize the variable fixing approach (cutting strategies) as follows.

4.3.1. Variable fixing approach (cutting strategies)

Consider branch $\mathcal{B} = \{\mathcal{B}^1, \mathcal{B}^2, \dots, \mathcal{B}^{|T|}\}$, where $\mathcal{B}^t = \left\{ \begin{matrix} w_{1i_1j_1}^t(\omega) & w_{1i_1j_2}^t(\omega) & \dots & w_{1i_1j_\ell}^t(\omega) & 0 & \dots & 0 \\ w_{2i_2j_1}^t(\omega) & w_{2i_2j_2}^t(\omega) & \dots & \vdots & 0 & \dots & 0 \\ \vdots & \vdots & \dots & w_{\mathcal{H}i_{\mathcal{H}}j_\ell}^t(\omega) & 0 & \dots & 0 \\ w_{|S|i_{|S|}j_1}^t(\omega) & w_{|S|i_{|S|}j_2}^t(\omega) & \dots & 0 & 0 & \dots & 0 \end{matrix} \right\}$. In \mathcal{B}^t ,

Input: Network topology and information of farmers, customers and potential hub facilities

Output: $S_1, f(S_1)$

Initialize:

Create a random solution S_0 by randomly select the p nodes as hub and assign farmers and customers to their nearest hubs.

Calculate the objective function of S_0 as $f(S_0)$

$neighborhood\ structure \leftarrow 1$

for it 1 to it^{max} **do**

if $neighborhood\ structure = 1$ **then**

$S_1 \leftarrow$ Randomly select a non-hub node and reassign it to a different hub in random order

else

$S_1 \leftarrow$ Randomly select a hub node and remove it from hub set and randomly select a non-hub node and reassign it to a different hub in random order

end if

Calculate the objective function of S_1 as $f(S_1)$

if $f(S_1) < f(S_0)$ **then**

$S_0 \leftarrow S_1$

$f(S_0) \leftarrow f(S_1)$

$neighborhood\ structure \leftarrow 1$

else

$neighborhood\ structure \leftarrow 2$

end

end

Fig. 3. The pseudo-code of the VNS algorithm for location of hub nodes and allocation of non-hub nodes to the hub.

$w_{\mathcal{H}i\mathcal{H}j\ell}^t(\omega)$ presents the amount of flow that farmer $\mathcal{H} \in S$ sends to customer $\ell \in D$, through origin hub facility $i_{\mathcal{H}}$ and destination hub facility j_{ℓ} that have been specified at step two of the B&C algorithm. Also, zero values are related to the non-assigned elements of \mathcal{B}^t . At this condition, for farmer $k \in S$, if the amount of distributed flow exceeded than its production capacity at time period t ($tp_{ki}(\omega)$), then the branch \mathcal{B} is pruned. Then we have:

$$\begin{aligned} w_{k\mathcal{H}i\ell}^t(\omega) &= 0, \forall k \in \{\mathcal{H} + 1, \dots, |S|\}, l = \ell \mid \sum_{l=1}^{\ell} w_{k\mathcal{H}i\ell}^t(\omega) > tp_{ki}(\omega), \forall k \in \{1, \dots, \mathcal{H}\}, t \in T \\ w_{k\mathcal{H}i\ell}^t(\omega) &= 0, \forall k \in S, l \in \{\ell + 1, \dots, |D|\} \end{aligned} \tag{62}$$

$$\begin{aligned} w_{k\mathcal{H}i\ell}^t(\omega) &= 0, \forall k \in \{\mathcal{H} + 1, \dots, |S|\}, l = \ell \mid \sum_{l=1}^{\ell-1} w_{k\mathcal{H}i\ell}^t(\omega) > tp_{ki}(\omega), \forall k \in \{\mathcal{H}, \dots, |S|\}, t \in T \\ w_{k\mathcal{H}i\ell}^t(\omega) &= 0, \forall k \in S, l \in \{\ell + 1, \dots, |D|\} \end{aligned} \tag{63}$$

In equations (62) and (63) when the value of a variable is determined as zero, it is equal to pruning whole possible sub-branches of current branch \mathcal{B} .

4.3.2. Lower bound estimation

Consider branch $\mathcal{B} = \{\mathcal{B}^1, \mathcal{B}^2, \dots, \mathcal{B}^{|\mathcal{T}|}\}$, where $\mathcal{B}^t = \left\{ \begin{matrix} w_{1i\mathcal{H}1}^t(\omega) & w_{1i\mathcal{H}2}^t(\omega) & \dots & w_{1i\mathcal{H}\ell}^t(\omega) & 0 & \dots & 0 \\ w_{2i\mathcal{H}1}^t(\omega) & w_{2i\mathcal{H}2}^t(\omega) & \dots & \vdots & 0 & \dots & 0 \\ \vdots & \vdots & \dots & w_{\mathcal{H}i\mathcal{H}\ell}^t(\omega) & 0 & \dots & 0 \\ w_{|S|i\mathcal{H}1}^t(\omega) & w_{|S|i\mathcal{H}2}^t(\omega) & \dots & 0 & 0 & \dots & 0 \end{matrix} \right\}$. At this

condition, the customers' demands of $\ell + 1$ to $|D|$ are not stratified. Moreover, customer's demand ℓ either has been met by means of current flow distribution set $\{w_{1i\mathcal{H}\ell}^t(\omega), w_{2i\mathcal{H}\ell}^t(\omega), \dots, w_{\mathcal{H}i\mathcal{H}\ell}^t(\omega)\}$ or not. So, to overcome this shortcoming, one possible lower bound can be estimated by relaxing the farmer's production capacity and allocating the customers' demands of set $\{\ell + 1, \dots, |D|\}$ to least cost path suppliers. Also, if customer ℓ has shortage demand, it would be satisfied by means of the mentioned estimation policy. So, we have:

$$w_{\mathcal{H}i\mathcal{H}\ell}^t(\omega) \leftarrow w_{\mathcal{H}i\mathcal{H}\ell}^t(\omega) + \max \left\{ 0, \mu_{\ell t} + \mathcal{Z} \Xi \sigma_{\ell t} - \sum_{k=1}^{\mathcal{H}} w_{k\mathcal{H}i\ell}^t(\omega) \right\} \tag{64}$$

Input: Network topology and information of farmers, customers and potential hub facilities

Output: $S_0, f(S_0)$

Initialize:

Create solution \mathcal{S} by supporting the customers' demands in ascending order though their nearest hubs

Calculate the objective function of S_0 as $f(S_0)$

neighborhood structure $\leftarrow 1$

for it 1 to it^{max} **do**

if *neighborhood structure* = 1 **then**

$S_1 \leftarrow$ Randomly select a customer in a random period and support its demand by a different farmers

if *neighborhood structure* = 2 **then**

$S_1 \leftarrow$ Randomly select two customers in a random period and swap farmers of the selected customers

if *neighborhood structure* = 3 **then**

$S_1 \leftarrow$ In a random period, randomly select a customer and randomly select one its farmers then add in add a random number in $[-m, m]$ to the amount of products that the select farmer sends to the select customer

Calculate the objective function of S_1 as $f(S_1)$

if $f(S_1) < f(S_0)$ **then**

$S_0 \leftarrow S_1$

$f(S_0) \leftarrow f(S_1)$

neighborhood structure $\leftarrow 1$

else

neighborhood structure \leftarrow *neighborhood structure* + 1

end

end

Fig. 4. The pseudo-code of the VNS algorithm for determining distribution policy of the poultry supply chain.

$$w_{\mathfrak{A}_l, i_{k,j,l}}^t(\omega) = \mu_{lt} + \mathcal{Z}_{\Xi} \sigma_{lt}, \forall l \in \{\ell + 1, \dots, |D|\} \tag{65}$$

where \mathfrak{A}_l is the supplier that has least distribution cost for supporting customer l . In equation (64), term $\max\{0, \mu_{\ell t} + \mathcal{Z}_{\Xi} \sigma_{\ell t} - \sum_{k=1}^{\mathcal{K}} w_{k,i_{k,j,\ell}}^t(\omega)\}$ ensures if flow distribution of current suppliers ($\sum_{k=1}^{\mathcal{K}} w_{k,i_{k,j,\ell}}^t(\omega)$) cannot satisfy demand of customer ℓ , the amount of demand shortage will be met by supplier \mathfrak{A}_{ℓ} .

4.3.3. Upper bound estimation (VNS Algorithm)

At this stage, VNS algorithm explores the search space to find a good solution for distribution policy of the poultry supply chain as a tight upper bound. The VNS algorithm pseudo code is presented in Fig. 4.

4.4. Step 4: Determining the amount of stock/pick up inventory for each farmer at each hub

At this step, the BB DP algorithm for each branch of step three applies a forward dynamic programming approach based on Wagner & Whitin (1958) to obtain the value of the amount of stock/pick up inventory for each farmer at each hub at each period. For this purpose, suppose \mathfrak{W}_{ab}^{ℓ} is the optimal cost of the poultry supply chain when demand of customers set $\ell \subset \mathcal{P}(D)$ in period $b|b > 1$ is satisfied in earlier period $a|a < |T| - 1$, where $\mathcal{P}(D)$ is whole possible subsets of customers set D . In this regard, at period a , suppose farmer \mathfrak{K} supports F^a fraction of demand of customer $l \in \ell$ and F^b fraction of this customer at period b . So, farmer \mathfrak{K} produces $w_{\mathfrak{K}, i_{\mathfrak{K}, j, l}}^a(\omega) = F^a(\mu_{la} + \mathcal{Z}_{\Xi} \sigma_{la}) + F^b(\mu_{lb} + \mathcal{Z}_{\Xi} \sigma_{lb})$ products for customer l at period a and delivers $F^a(\mu_{la} + \mathcal{Z}_{\Xi} \sigma_{la})$ products to customer l and stocks $F^b(\mu_{lb} + \mathcal{Z}_{\Xi} \sigma_{lb})$ products at its destination hub i_l at this period (i. e, $S_{\mathfrak{K}, i_{\mathfrak{K}, j, l}}^a = F^b(\mu_{lb} + \mathcal{Z}_{\Xi} \sigma_{lb})$). So at period b farmer \mathfrak{K} pickups the inventories that were stocked at period \mathfrak{K} . Therefore, $\mathfrak{W}_{ab}^{\ell} \{S_{1, i_{1, j, \ell}}^a, \dots, S_{k, i_{k, j, \ell}}^a, \dots, S_{|S|, i_{|S|, j, \ell}}^a\}$ shows the poultry supply chain costs, when demand of customers' set $\ell \subset \mathcal{P}(D)$ in period b is satisfied from earlier period a , regarding farmers' stock ($S_{1, i_{1, j, \ell}}^a, \dots, S_{|S|, i_{|S|, j, \ell}}^a$), pickup ($S_{1, i_{1, j, \ell}}^b, \dots, S_{|S|, i_{|S|, j, \ell}}^b$) inventory policies and can be calculated by optimizing sub-problem B.

Sub-problem B

$$\min \mathfrak{W}_{ab}^{\ell} \{S_{1, i_{1, j, \ell}}^a(\omega), \dots, S_{k, i_{k, j, \ell}}^a(\omega), \dots, S_{|S|, i_{|S|, j, \ell}}^a(\omega)\} = \sum_{\omega \in \Omega} Pr_{\omega} \beta(x, \omega) | t = a, b; H \tag{66}$$

$$= \mathcal{H}; \ell \subset \mathcal{P}(D)$$

Subject to:

$$(27), (32)-(50), (53)-(56) | t = a, b; H = \mathcal{H}, \ell \subset \mathcal{P}(D)$$

$$\sum_{k \in S} w_{k, i_{k, j, l}}^a(\omega) + \sum_{k \in S} df_{kl}^a(\omega) \geq \mu_{la} + \mathcal{Z}_{\Xi} \sigma_{la}, i_{k, j, l} \in \mathcal{H}, \forall l \in D \tag{67}$$

$$\sum_{k \in S} w_{k, i_{k, j, \ell}}^b(\omega) + \sum_{k \in S} df_{k\ell}^b(\omega) = \mu_{\ell b} + \mathcal{Z}_{\Xi} \sigma_{\ell b} - \sum_{k \in S} S_{k, i_{k, j, \ell}}^a(\omega), i_{k, j, \ell} \in \mathcal{H} \tag{68}$$

$$\sum_{k \in S} w_{k, i_{k, j, l}}^b(\omega) + \sum_{k \in S} df_{kl}^b(\omega) \geq \mu_{lb} + \mathcal{Z}_{\Xi} \sigma_{lb}, \forall l \in D \setminus \ell, i_{k, j, \ell} \in \mathcal{H} \tag{69}$$

$$fip_{ka}(\omega) = tp_{ka}(\omega) - w_{k, i_{k, j, \ell}}^a(\omega) - df_{kl}^a(\omega), i_{k, j, \ell} \in \mathcal{H}, \forall k \in S \tag{70}$$

$$\sum_{k \in S} S_{k, i_{k, j, \ell}}^a(\omega) \leq \min \left\{ \sum_{k \in S} fip_{ka}(\omega), \mu_{\ell b} + \mathcal{Z}_{\Xi} \sigma_{\ell b} \right\}, i_{k, j, \ell} \in \mathcal{H} \tag{71}$$

$$S_{k, i_{k, j, \ell}}^a(\omega) \leq fip_{ka}(\omega), i_{k, j, \ell} \in \mathcal{H}, \forall k \in S \tag{72}$$

$$S_{k, i_{k, j, \ell}}^b(\omega) = S_{k, i_{k, j, \ell}}^a(\omega), i_{k, j, \ell} \in \mathcal{H}, \forall k \in S \tag{73}$$

$$S_{k, i_{k, j, \ell}}^a(\omega) \geq 0, i_{k, j, \ell} \in \mathcal{H}, \forall k \in S \tag{74}$$

The objective function of the sub-problem two is calculated according to equation (53), while hub set \mathcal{H} and allocation structure of farmers/customers to set hub \mathcal{H} at periods a, b are specified by means of steps one and two of BB DP algorithm. Constraint (67) determines that the customers' demands are met at period a . Constraint (68) implies, unsatisfied demands of customers set ℓ should be met at period b . Also for customers who are not at set ℓ , whole their demand need to be satisfied by constraint (69). Constraint (70)

calculates the free production capacity for each farmer at period α . According to constraint (71), the amount of stock-inventories at whole hubs should not be longer than both total free production capacities of farmers and demand of customers' set ℓ . Constraint (72) ensures the amount of stock-inventory for each farmer cannot exceed its free production capacity. Constraint (73) indicates that the amount of stock-inventory for each farmer at its origin hub at period α is the same with the pickup-inventory for that farmer at period b . This is due to the fact that the sub-problem two aims at satisfying the demand of customers' set ℓ of period b in earlier period α . Every time that the BBDD algorithm needs to optimize sub-problem two, it applies step 3.

Now, by means of recursive cost function, the optimal poultry supply chain costs up to period α ($\mathcal{W}^*(\alpha)$) can be calculated as follows.

$$\mathcal{W}^*(\alpha) = \min \left\{ \mathcal{W}^*(\alpha - 1) + \mathcal{W}_{ab}^{\alpha} \left\{ S_{1/\ell/\ell}^{\alpha}(\omega), \dots, S_{k/\ell/\ell}^{\alpha}(\omega), \dots, S_{|S|/\ell/\ell}^{\alpha}(\omega) \right\} \mid \forall b \in \{\alpha + 1, \dots, |T|\}, \ell \subset \mathcal{P}(D) \right\}, \tag{75}$$

It should be noted that $\mathcal{W}^*(0) = 0$. According to equation (75), the value of $\mathcal{W}_{ab}^{\alpha} \left\{ S_{1/\ell/\ell}^{\alpha}(\omega), \dots, S_{k/\ell/\ell}^{\alpha}(\omega), \dots, S_{|S|/\ell/\ell}^{\alpha}(\omega) \right\}$ for given period b , need to be calculated when customer set ℓ includes whole possible sub-sets of customer set D (i.e. $\mathcal{P}(D)$).

5. Case study

According to the National Chicken Council (2021), U.S. has the largest broiler chicken industry in the world, and its strategies against COVID-19 would provide a reliable road map for other countries. Due to the convenient geographical location, accessing to different transportation modes (water, rail, land), weather condition and close distance to Mexico and Cuba (among top 3 export destinations), the state of Mississippi is among top 5 broiler producers in US. Hence, in this section, to validate the proposed poultry supply chain, we perform a case study of poultry industry in the state of Mississippi. Mississippi generates \$18.36 billion in total economic activities and provides 72,153 total jobs. With such an economic impact, studying the poultry supply chain in Mississippi is of a great importance. Based on Mississippi Poultry Association, there are over 1,700 family-run broiler producers. It is almost impossible to study the effect of COVID-19 on all these farmers at the same time. However, considering the size of the industry, professionalism and access to information, in this study, we focus on Peco Foods, Koch Foods and Marshall Durbin Companies as three major poultry farmers in the state of Mississippi.

We select Jackson, Lake Charles, Tallahassee and Orlando as major domestic consumers and Havana (in Cuba) and Monterrey (in Mexico) as international customers. It should be noted that Mexico and Cuba are among the top broiler meat importers from Mississippi (Tabler, 2017). The boiler meat supply chain is studied under realistic data scenarios. Three time periods during one year (four months per each period) are considered. To investigate the pandemic effect on the proposed poultry supply chain, low and severe pandemic conditions are analyzed. In this section, firstly the parameters and data collection procedure are described; then the computational results will be discussed.

5.1. Parameters description and data collection

Based on the information provided by Citizens for a Better Eastern Shore Community (CBES) (CBES, 2020), Peco Foods, Koch Foods and Marshall Durbin Companies are among the largest broiler producers (farmers) in broiler industry at Mississippi, which will play farmers role in the proposed supply chain network. To facilitate distribution process of broilers meat among domestic and international customers, nine potential hub facility locations are selected which are Huston Amtrak Station, Port of Tampa, Jackson Canadian National Railway, Port of New Orleans, Jacksonville Amtrak Station, Natchez port, Port of Brownsville, Havana Port and Tuxpan Port Terminal. To better address the supply chain segments (farmers, customers and hubs), specific numbers are assigned to each of them that can be seen in Table 2.

To calculate the distance among the supply chain segments, we studied the distance index from three criteria of land, rail and sea. For attaining the rail information, The North America Railroads data set is applied (The North America Railroads, 2020). The information of sea distance among the ports of the proposed broiler supply chain at Mississippi state is calculated by <https://sea-distances.org/>. Moreover, the information of Great River Road is used for determining the Mississippi river path (FHWA, 2020).

Table 2
The broiler supply chain's segments.

Farmers		Hub candidate locations			Customers		
Producer	Number	Candidate facility	State	Number	Area	State	Number
Peco Foods	1	Huston Amtrak Station	Rail station	4	Lake Charles	Louisiana, US	13
Koch Foods	2	Port of Tampa	Port/ Rail station	5	Orlando	Florida, US	14
Marshall Durbin Companies	3	Jackson Canadian National Railway	Rail station	6	Tallahassee	Florida, US	15
		Port of New Orleans	Port /Rail station	7	Jackson	Mississippi, US	16
		Jacksonville Amtrak Station	Rail station	8	Monterrey	Mexico	17
		Natchez port	Port	9	Havana	Cuba	18
		Port of Brownsville	Port	10			
		Havana Port Terminal	Port	11			
		Tuxpan Port	Port	12			

The average price of moving one ton freight per km by a 20 tons truck is \$0.1069, by rail \$0.03493 and by barge is \$0.00916 (Austin, 2016; Young et al., 2005). Moreover, the transportation capacity for each truck, railcar and barge is 20, 200 and 1500 tons, respectively. Fig. 5 shows the geographical positions of farmers, customers and potential hub facilities, which is created by ArcGIS 10.8.

According to the CBES information, broiler producers use poultry houses which in average have 66 feet wide and 600 feet long and can hold 50,000 birds per crop. However, due to poultry diseases, the production rate has 3% to 5% loss (CBES). As thus, with average five crops per year, each poultry produces [237500, 242500] birds per year. Generally, a broiler has 1.905 kg (4.2 lbs) weight. Therefore, each poultry house can produce [452.6, 462] tons broiler meat per year or [150.8, 154.0] tons per every four months (one time period in this broiler supply chain). According to (ThePoultrySite, 2020), the production cost of each broiler pound was 86.5 cents in 2020, which means one ton broiler meat has 1907\$ cost.

To obtain demand of domestic and international customers, we used the index of poultry consumption per capita (PCPC) that its value per each year for different countries are addressed at www.statista.com. The poultry consumption during 2019 for every American was 49.26 kg poultry meat, for every Mexican was 29.25 kg and for every Cuban was 19.84 kg. Now, by multiplying the PCPC index in population of each area, its broiler meat demand can be estimated. It should be noted, the production rate and consumption pattern are affected by seasonal variations (Patra et al., 2017). Kalhor et al. (2016) showed that during cold weather broiler meat production and consumption rate is higher than hot months, up to 20%. Since, the proposed poultry supply chain includes three time periods, the maximum production capacity and consumption rate is in the cold months from November to February (second time period). So, according to Kalhor et al. (2016), the production capacity and consumption rate during March to June (first time period) and July to October (third time period) can be estimated as 90% and 80% of cold months (November to February), respectively. Table 3 shows the farmers' production and customers demand information based upon the provided information. To define scenarios of production rate ($\hat{I}_{tk}(\omega)$), both seasonal variations and poultry diseases are included. In this regard, 30 scenarios of farmers' production rates were defined according to Table 3. For each problem solving, the model is optimized under all scenarios and the average of the obtained results will be displayed. The cost of freezing and cold storage is 2.16 US \$/ton/day (Fao, 2020). In addition, we assumed the penalty cost of one ton broiler shortage is doubled of its production cost.

5.2. Computational results

In this section the results of optimizing the broiler supply chain in Mississippi under pandemic condition are presented. For coding BBDP approach, MATLAB 2016a is applied and to validate the proposed solution procedure, we compare it with COIN-OR Branch and Cut (CBC) and CPLEX solvers. CBC is selected because it is less heavy weight than general Branch and Cut (BC) framework, which enables CBC to act faster than Branch-Cut-Price (BCP) and Symphony algorithms (<https://www.coin-or.org/>). CPLEX solver also is selected as it has more robust performance and acts faster (www.ibm.com). We coded CPLEX and CBC solvers in GAMS 24.1.2. The whole algorithms were executed on a computer with 4 GB RAM and Intel Core i5 2.5 GHZ CPU. To investigate the performance of the proposed models (Model 1 and Model 2) for controlling the pandemic effect and also for validating BBDP model, we design a set of experiments based upon the described data of broiler supply chain in Mississippi State.

5.2.1. Measuring the efficiency of stocking Farmers' products at destination hubs

To measure the effectiveness of stocking the farmers' productions at the destination hubs for mitigating the pandemic consequences, firstly we reformat Model 1, when stocking policy is not permitted and consequently there is no sign of inventory variables ($S_{kijl}^t(\omega) = 0, \hat{S}_{kijl}^t(\omega) = 0, I_{ijkp}^t(\omega) = 0$). The new model that supports only indirect logistic policy and does not include inventory policy is named *Model 1 without inventory policy* in the following. Table 4 shows the obtained results of comparing Model 1 with and without inventory policy. In Table 4, the fourth column shows the pandemic effect on accessibility level to the customers. We define two scenarios, i.e., low and severe pandemic where in the first time period there is no sign of pandemic and in the second and third periods

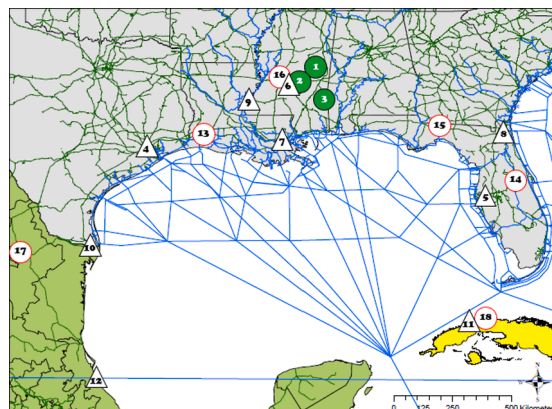


Fig. 5. The geographical viewpoint of the broiler supply chain under pandemic.

Table 3
Information about farmers' production and customers demand in the proposed broiler supply chain.

		$t = 1$		$t = 2$		$t = 3$	
Customers		μ_{1t} (ton)	σ_{1t} (ton)	μ_{2t} (ton)	σ_{2t} (ton)	μ_{3t} (ton)	σ_{3t} (ton)
Lake Charles	Domestic	525.44	0	656.8	0	591.12	0
Orlando		1313.6	0	1642	0	1477.8	0
Tallahassee		2627.2	0	3284		2955.6	0
Jackson		1050.88	0	1313.6	0	1182.24	0
Monterrey	International	5460	1092	6825	1365	6142.5	1228.5
Havana		2645.333	529.0667	3306.667	661.3333	2976	595.2
Farmers		\mathcal{L}_{1k}	$\tilde{I}'_{1k}(\omega)$	\mathcal{L}_{2k}	$\tilde{I}'_{2k}(\omega)$	\mathcal{L}_{3k}	$\tilde{I}'_{3k}(\omega)$
Peco Foods		75	[135.7, 135.8, 135.9, ..., 138.6]	75	[150.8, 150.9, 160.0, ..., 154.0]	75	[120.7, 120.8, 120.9, ..., 123.2]
Koch Foods		150	[135.7, 135.8, 135.9, ..., 138.6]	150	[150.8, 150.9, 160.0, ..., 154.0]	150	[120.7, 120.8, 120.9, ..., 123.2]
Marshall Durbin Companies		100	[135.7, 135.8, 135.9, ..., 138.6]	100	[150.8, 150.9, 160.0, ..., 154.0]	100	[120.7, 120.8, 120.9, ..., 123.2]

$$\sigma_{lt} = 0.2\mu_{lt}$$

pandemic occurs. Thus, under low pandemic we can define *ACPE* values in three time periods for domestic and international customers as a (2×4) -matrix of $\begin{bmatrix} DC & 1 & 0.9 & 0.8 \\ IC & 1 & 0.8 & 0.7 \end{bmatrix}$, where column one shows the type of customers, column two to four show the *ACPE* values for first to third periods, respectively. Value 0.8 in first row and third column means that 80% of domestic customers can be accessed in the third period. In a similar definition, *ACPE* parameter is defined under severe pandemic by a (2×4) -matrix of $\begin{bmatrix} DC & 1 & 0.5 & 0.2 \\ IC & 1 & 0.4 & 0.1 \end{bmatrix}$. The fifth column shows the pandemic effect on the transportation modes (*VPE*) under low and severe conditions as a three elements vector. Frist to third element correspond to pandemic effect on first to third time periods. Under low pandemic scenario, vector of [1, 0.9, 0.8] shows that in the first period (where there is no pandemic) all transportation modes are fully accessed. In the second and third periods 90% and 80% of transportation modes are available. For severe pandemic, we show *VPE* by [1, 0.5, 0.2]. In a similar way, the impact of pandemic on farmers production rate is shown in the sixth column under low ([1, 0.9, 0.8]) and severe ([1, 0.5, 0.2]) scenarios. Column seven indicates that the results of Model 1 with or without inventory policy. Columns eight presents the objective function of optimizing Model 1 with and without inventory policy by CPLEX solver. Column nine shows the CPU time of CPLEX algorithm. Columns ten and eleven represent value of objective function of Model 1 solved by BB DP and corresponding CPU time. Column twelve shows the objective function value of Model 1 obtained by CBC algorithm. We restrict the CBC algorithm to obtain the solutions up to 11,000 s. The CBC's CPU time is presented in column thirteen. The absolute gap between CPLEX and BB DP is presented in column fourteen, and the absolute gap between CBC and BB DP is shown in column fifteen. Column sixteen shows the absolute gap among Model 1 with or without inventory policy ($GAP_M\%$). Equations (76) calculates the values of $GAP_A^i\%$

$$GAP_A^i\% = \frac{Obj_{Model1withinventorypolicy}^{BB DP} - Obj_{Model1withinventorypolicy}^i}{Obj_{Model1}^i} \times 100, \tag{76}$$

$i = CPLEX, CBC$

$$GAP_M\% = \frac{Obj_{Model1withoutinventorypolicy} - Obj_{Model1withinventorypolicy}}{Obj_{Model1withinventorypolicy}} \times 100 \tag{77}$$

The obtained results of Table 4 shows that the proposed stocking policy of farmers' productions during pre-pandemic effectively controlled the negative pandemic consequences on the economy of the broiler supply chain. The stocking policy saved the total costs up to 23.5539 % under severe pandemic. This is due to the fact that during pandemic the whole parts of the broiler supply chain from production rate to distribution segments and access to the customers (especially international ones) are affected. Therefore, satisfying the customers' demand in such tough situations is practically impossible and consequently leads to customers' shortage.

On the contrary, during the first period, farmers can produce whole or a fraction of customers' demands of second and third periods and stock them in the destination hubs, which are close enough to the customers to support them during pandemic. As an example, we analyze scenario 3 and scenario 4, in detail. For this purpose, Fig. 6 depicts the network configuration of the proposed broiler supply chain for scenario 3 (Fig. 6.a) and scenario 4 (Fig. 6.b). According to Fig. 4.a, Port of Tampa (node 5), Natchez port (node 9), Port of Brownsville (node 10) and Havana Port Terminal (node 11) are selected as hub facilities. Peco Foods (farmer 1) and Koch Foods (farmer 2) are assigned to the Natchez port and Marshall Durbin Companies (farmer 3) is allocated to Port of Brownsville. The areas of Lake Charles (node 13) and Jackson (node 16) are supported by Natchez port (node 9), Tallahassee (node 15) and Orlando (node 14) are allocated to Port of Tampa (node 5), Monterrey (node 17) is assigned to Port of Brownsville (node 10) and Havana (node 18) is supported by Havana Port Terminal (node 18).

Table 4

Comparing the results of optimizing the broiler supply chain under pandemic at Mississippi State by CPLEX, CBC and BBDDP algorithms when inventory policy is permitted and not permitted for indirect logistic.

Scenario	NHF	Ξ	Pandemic Severity Effects on Customers	Pandemic Effects on Transportation Modes	Pandemic Severity Effects on Production	Inventory policy	CPLEX		BBDDP		CBC		GAP _A ^{CPLEX} %	GAP _A ^{CBC} %	GAP _M %
							Obj*	CPU	Obj	CPU	Obj	CPU			
1	4	0.99	[DC 1 0.9 0.8]	[1, 0.9, 0.8]	[1, 0.9, 0.8]	permitted	331,753,533	7414	337,035,049	200	333,058,716	11,000	1.592	1.194	0.000
2	4	0.99	[IC 1 0.8 0.7]			not permitted	331,753,533	8235	333,213,249	212	334,147,954	11,000	0.440	-0.28	
3	4	0.99	[DC 1 0.5 0.2]	[1, 0.5, 0.2]	[1, 0.5, 0.2]	permitted	338,273,198	9839	342,897,393	216	342,847,914	11,000	1.367	0.014	23.554
4	4	0.99	[IC 1 0.4 0.1]			not permitted	417,949,574	8969	425,861,359	216	422,776,773	11,000	1.893	0.3	
5	4	0.90	[DC 1 0.9 0.8]	[1, 0.9, 0.8]	[1, 0.9, 0.8]	permitted	330,976,493	9720	335,616,783	213	331,185,501	11,000	1.402	1.338	0.002
6	4	0.90	[IC 1 0.8 0.7]			not permitted	330,981,646	7779	333,708,935	216	331,742,249	11,000	0.824	0.593	
7	4	0.90	[DC 1 0.5 0.2]	[1, 0.5, 0.2]	[1, 0.5, 0.2]	permitted	331,090,533	9952	336,530,350	215	335,957,023	11,000	1.643	0.171	21.622
8	4	0.90	[IC 1 0.4 0.1]			not permitted	402,677,900	9785	407,059,036	204	405,898,107	11,000	1.088	0.286	
9	4	0.50	[DC 1 0.9 0.8]	[1, 0.9, 0.8]	[1, 0.9, 0.8]	permitted	330,262,645	8671	332,240,918	208	332,054,128	11,000	0.599	0.056	0.001
10	4	0.50	[IC 1 0.8 0.7]			not permitted	330,267,273	8451	334,385,706	205	331,874,554	11,000	1.247	0.757	
11	4	0.50	[DC 1 0.5 0.2]	[1, 0.5, 0.2]	[1, 0.5, 0.2]	permitted	327,224,893	8118	330,752,377	210	329,139,278	11,000	1.078	0.490	17.312
12	4	0.50	[IC 1 0.4 0.1]			not permitted	383,875,518	8104	388,178,763	215	387,877,936	11,000	1.121	0.078	
13	3	0.99	[DC 1 0.9 0.8]	[1, 0.9, 0.8]	[1, 0.9, 0.8]	permitted	332,662,789	5839	338,517,654	205	332,662,789	8984	1.76	1.76	0.000
14	3	0.99	[IC 1 0.8 0.7]			not permitted	332,662,789	5044	335,503,729	213	332,662,789	9333	0.854	0.854	
15	3	0.99	[DC 1 0.5 0.2]	[1, 0.5, 0.2]	[1, 0.5, 0.2]	permitted	345,119,416	6662	347,521,447	219	345,119,416	9012	0.696	0.696	21.355
16	3	0.99	[IC 1 0.4 0.1]			not permitted	418,820,287	7271	422,262,990	219	420,848,579	11,000	0.822	0.336	
17	3	0.90	[DC 1 0.9 0.8]	[1, 0.9, 0.8]	[1, 0.9, 0.8]	permitted	332,037,012	5648	333,192,501	208	332,037,012	10,015	0.348	0.348	0.000
18	3	0.90	[IC 1 0.8 0.7]			not permitted	332,037,012	7903	337,439,254	202	336,147,924	11,000	1.627	0.384	
19	3	0.90	[DC 1 0.5 0.2]	[1, 0.5, 0.2]	[1, 0.5, 0.2]	permitted	338,445,613	7314	339,098,813	217	339,790,216	11,000	0.193	-0.204	19.245
20	3	0.90	[IC 1 0.4 0.1]			not permitted	403,580,224	7721	411,119,103	208	409,057,189	11,000	1.868	0.504	
21	3	0.50	[DC 1 0.9 0.8]	[1, 0.9, 0.8]	[1, 0.9, 0.8]	permitted	331,332,020	7386	336,497,486	220	335,077,489	11,000	1.599	0.424	0.003
22	3	0.50	[IC 1 0.8 0.7]			not permitted	331,342,256	6485	333,350,190	208	331,342,256	11,000	0.606	0.606	
23	3	0.50	[DC 1 0.5 0.2]	[1, 0.5, 0.2]	[1, 0.5, 0.2]	permitted	334,476,967	5924	335,383,400	200	334,476,967	9807	0.271	0.271	15.096
24	3	0.50	[IC 1 0.4 0.1]			not permitted	384,970,650	5818	387,080,289	216	384,970,650	11,000	0.548	0.548	

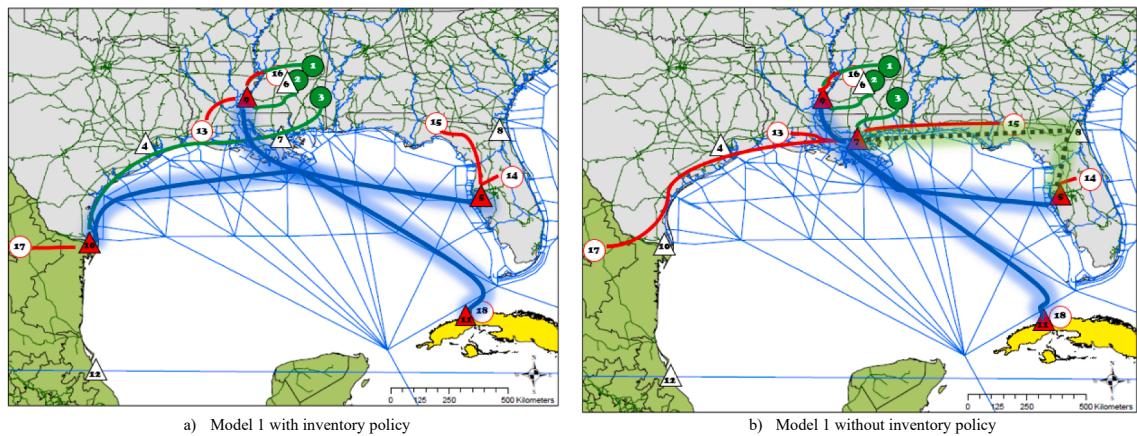


Fig. 6. Comparing network configuration of Model 1 when inventory policy is permitted and not permitted.

In Fig. 6, the whole inter-hub routes are supported by ship transportation mode (thick blue lines). The first reason is because higher capacity and lower transportation cost of ships compare with railway network. The second reason relates to stocking policy of farmers' production during pre-pandemic which enables them to transport most of products by ship. To further analyze the second reason, we investigate the inventory variables of the described supply chain by Table 5. Since first time period was pre-pandemic, farmers stocked most of customers' demands of second and third periods, where pandemic occurred. For example, consider Orlando as a major domestic customer. During first period, Koch Foods stocked 1649.476 tons broiler meat in Tampa port, the place that is so close to Orlando city, and released 831.676 and 817.800 tons of stocked inventories in the second and third periods, respectively. By this strategy, in pre-pandemic period, Koch Foods helped the broiler supply chain to supply 50.65% and 55.33% of Orlando demands in second and third period, respectively.

Stocking products is not permitted in scenario 4 as reflected in Fig. 6.b. Since access to the ships during severe pandemic is restricted and there is no chance of supplying customer demands in prior periods, the interaction among Tampa and New Orleans is handled by railway (green thick dashed line). As railway has higher cost than ship, this change in turn increases total costs. To mitigate the supply chain cost in scenario 4, New Orleans plays a vital role since it is placed in the middle of the broiler supply chain network

Table 5
Inventory policy variables in scenario 3.

Hub facility	Customers	\bar{S}_{ijkp}^t			\bar{S}_{ijkp}^{-t}			Shortage		
		$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$
Tampa	14	1649.476 (Farmer 2)	0	0	0	831.676 (Farmer 2)	817.800 (Farmer 2)	0	0	0
	15	0	2955 (Farmer 1)	0	0	0	2955 (Farmer 1)	0	0	0.600
Hub facility	Customers	\bar{S}_{ijkp}^t			\bar{S}_{ijkp}^{-t}			Shortage		
		$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$
Natchez	13	806.800 (Farmer 2)	0	0	0	656.800 (Farmer 2)	150.000 (Farmer 2)	0	0	1.120
	16	244.603 (Farmer 1) +370.452 (Farmer 2)	567.185 (Farmer 2)	0	0	0	244.603 (Farmer 1) +937.637 (Farmer 2)	0	0	0
Hub facility	Customers	\bar{S}_{ijkp}^t			\bar{S}_{ijkp}^{-t}			Shortage		
		$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$
Brownsville	17	9004.905 (Farmer 1) +7750.438 (Farmer 3)	0	0	0	7750.438 (Farmer 3)	9004.905 (Farmer 1)	0	0	0
	Hub facility	Customers	\bar{S}_{ijkp}^t			\bar{S}_{ijkp}^{-t}			Shortage	
Havana	18	\bar{S}_{ijkp}^t			\bar{S}_{ijkp}^{-t}			Shortage		
		$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$
		9210.375 (Farmer 2)	0	0	0	4847.559 (Farmer 2)	4362.816 (Farmer 2)	0	0	0

and not only can support ships, but also permits rail system to transports farmers’ products to customers. However, this stagey could not effectively support customers, especially international ones. As can be seen in Fig. 6.b, there is neither ship nor rail way to support Monterrey and sever pandemic restricted mass transportation to this city. Table 6 shows the customers shortage in different periods. The whole Monterrey’s demand in the second and third period and entire Havana’s demand in third are missed. In other words, in scenario 4 since there was no preventive policy, an overall of 28302.18 tons of customers’ demands are missed during pandemic, which imposes a large amount of penalty costs to the broiler supply chain. Another important issue that can be concluded from Table 4 shows the high performance of BBDDP algorithm in solving the broiler supply chain optimization problem. The maximum gap between BBDDP and CPLEX is 1.868%, and between BBDDP and CBC is 1.76%. In terms of the CPU time, BBDDP solution procedure is up to 46 times faster than CPLEX and at least 43 times faster than CBC, which shows the time superiority of the proposed BBDDP algorithm.

5.2.2. Measuring the efficiency of direct transportation possibility among farmers and customers

In this section, we investigate the impact of having direct access to customers along with multi-modal transportation system on the broiler supply chain at Mississippi State. For this purpose, by removing scenarios that were related to Model 1 without inventory policy, Table 7 compares 12 remaining scenarios of Model 1 (with inventory policy), which supports only indirect logistics with Model 2, where both direct and indirect logistics are included. The obtained results in Table 7 show that providing direct logistic for farmers enables the broiler supply chain to save costs up to 7.304%. To better analyze this issue, we investigate the information of scenario 2 in Table 6 (which is the same as information of scenario 3 and scenario 4 in Table 3) in detail. The inventory variables of Model 2 for scenario 2 in Table 7 are presented in Table 8 and the amount of direct flow transportation of this scenario is shown in Table 9. According to Table 8 and Table 9, since farmers accessed to direct logistic, which is not only faster and easier than ship and railway modes, but also has fewer restrictions during pandemic, they stocked only international customers’ demands in hub facilities and land transportation by truck was replaced of ship to cover domestic customers. Fig. 7 shows the network configuration of scenario 2 in Table 7 for Model 2. According to Fig. 7.b, during pandemic (second and third periods), along with using stocked products at hub centers, direct logistic supported all customers except Havana (since there is no direct path from farmers to this city). As an important consequence, although mass transportation has economy of scale, during pandemic that having access to different parts of supply chain is difficult, using direct logistic by truck can be a suitable alternative. The values of $GAP_A^{CPLEX}\%$ and $GAP_A^{CBC}\%$ in Table 7 show that BBDDP algorithm has at most 4.515% and 4.024% gap compared with the CPLEX and CBC algorithms, respectively. Furthermore, BBDDP is up to 33 times faster than CPLEX and at least 32 times faster than CBC for solving Model 2.

5.3. Sensitivity analysis

In this section, we imply sensitivity analysis on the maximum available barges in the broiler supply chain and the minimum fraction of inter-hub transportation that should be handled by barge to use the economy advantageous of waterways (ϑ) especially at Mississippi river. We set experiments for both Model 1 and Model 2 when $NHF = 4, \Xi = 0.99, \vartheta \in \{0.2, 0.5, 0.8\}, Vmax_q^1 \in \{5, 10, 15, 20\}$ and we have severe pandemic during the second and third periods ($ACPE = \begin{bmatrix} DC & 1 & 0.5 & 0.2 \\ IC & 1 & 0.4 & 0.1 \end{bmatrix}, VPE = [1, 0.5, 0.2], MPE^t = [1, 0.5, 0.2]$).

Fig. 8 presents the obtained results of the described experiments. According to Fig. 8, in Model 1 and Model 2, there is a little gap among total costs of different scenarios when there are 15 barges and more, regardless of ϑ value. Moreover, when models are less restricted to select ship mode, ($\vartheta \in \{0.2, 0.5\}$) in both models, the objective function values of all scenarios are so close to each other even for 10 barges. It indicates that there is no need to enforce the modes to more select water paths and when there are enough barges in the broiler supply chain, both models always prefer ship to rail for inter-hub paths, due to its higher capacity and fewer transportation costs.

In addition, Model 2 in all scenarios had better performance compared with Model 1, even for limited available barges. Table 10 presents the shortage values of customers’ demands in different periods for Model 1 and Model 2, when there is only 5 barges and $\vartheta \in \{0.2, 0.5, 0.8\}$. Thus, during pandemic that accessing to ship or rail mode is difficult, customers are supported by trucks in overland routes. Even under severe pandemic, Model 2 has an acceptable number of customers’ unsatisfied demands. Table 10 shows Model 2 had at most 9732.190 tons shortage when the pandemic was so severe ($t = 3$) and $\vartheta = 0.8$. Most of this shortage relates to Havana, where the only way for transporting products is shipping mode. Although 5 barges are not enough for supporting whole the customers’ demands like Havana, Model 2 has overcome this shortcoming by allocating whole ship transportation mode capacity to international customers and supporting domestic ones either directly by truck or indirectly by railway network (Fig. 9.b). On the contrary, in similar conditions, Model 1 had 46629.660 tons customers’ demands shortage. In Fig. 9.a, Model 1 neither support international customers like Havana and Monterrey, nor properly support domestic customers like Orlando. This is because that Model 1 had to use only

Table 6
Shortage values in scenario 4.

Customer	13	14	15	16	17	18
First period	0	0	0	0	0	0
Second period	3.3	17	0	1.1	10005.45	347.559
Third period	111.12	1477.8	2955.6	15.533	9004.905	4362.816

Table 7

Comparing the results of optimizing the broiler supply chain under pandemic at Mississippi State by CPLEX, CBC and BBDP algorithms when there is only indirect logistic (Model 1) and when both the direct and indirect logistic are involved (Model 2)

Scenario	#DC	Ξ	Pandemic Severity Effects on Customers			Pandemic Effects on Transportation Modes	Pandemic Severity Effects on Production	Model 1		Model 2		BBDP		CBC		$GAP_A^{CPLEX}\%$	$GAP_A^{CBC}\%$	$GAP_M\%$	
								Obj*	CPU	Obj*	CPU	Obj	CPU	Obj	CPU				
1	4	0.99	DC	1	0.9	0.8	[1, 0.9, 0.8]	[1, 0.9, 0.8]	331,753,533	7414	331,135,267	9968	344,936,985	331	339,741,560	11,000	4.168	1.529	0.187
			IC	1	0.8	0.7													
2	4	0.99	DC	1	0.5	0.2	[1, 0.5, 0.2]	[1, 0.5, 0.2]	338,273,198	9839	321,628,179	10,183	329,093,169	330	333,220,284	11,000	2.321	-1.239	5.175
			IC	1	0.4	0.1													
3	4	0.90	DC	1	0.9	0.8	[1, 0.9, 0.8]	[1, 0.9, 0.8]	330,976,493	9720	330,521,110	9915	339,745,954	310	340,113,778	11,000	2.791	-0.108	0.138
			IC	1	0.8	0.7													
4	4	0.90	DC	1	0.5	0.2	[1, 0.5, 0.2]	[1, 0.5, 0.2]	331,090,533	9952	318,898,638	11,014	331,839,545	341	321,214,019	11,000	4.058	3.308	3.823
			IC	1	0.4	0.1													
5	4	0.50	DC	1	0.9	0.8	[1, 0.9, 0.8]	[1, 0.9, 0.8]	330,262,645	8671	329,862,913	9855	336,796,631	311	334,217,841	11,000	2.102	0.772	0.121
			IC	1	0.8	0.7													
6	4	0.50	DC	1	0.5	0.2	[1, 0.5, 0.2]	[1, 0.5, 0.2]	327,224,893	8118	316,127,838	10,574	328,829,855	340	330,755,433	11,000	4.018	-0.582	3.510
			IC	1	0.4	0.1													
7	3	0.99	DC	1	0.9	0.8	[1, 0.9, 0.8]	[1, 0.9, 0.8]	332,662,789	5839	331,263,651	7476	343,884,796	321	334,287,991	11,000	3.81	2.871	0.422
			IC	1	0.8	0.7													
8	3	0.99	DC	1	0.5	0.2	[1, 0.5, 0.2]	[1, 0.5, 0.2]	345,119,416	6662	321,628,179	7335	336,149,691	319	323,147,887	11,000	4.515	4.024	7.304
			IC	1	0.4	0.1													
9	3	0.90	DC	1	0.9	0.8	[1, 0.9, 0.8]	[1, 0.9, 0.8]	332,037,012	5648	330,697,987	7007	341,568,030	318	336,144,235	11,000	3.287	1.614	0.405
			IC	1	0.8	0.7													
10	3	0.90	DC	1	0.5	0.2	[1, 0.5, 0.2]	[1, 0.5, 0.2]	338,445,613	7314	318,898,638	7704	328,366,739	311	325,445,674	11,000	2.969	0.898	6.130
			IC	1	0.4	0.1													
11	3	0.50	DC	1	0.9	0.8	[1, 0.9, 0.8]	[1, 0.9, 0.8]	331,332,020	7386	330,064,830	7432	341,009,780	312	331,015,567	11,000	3.316	3.019	0.384
			IC	1	0.8	0.7													
12	3	0.50	DC	1	0.5	0.2	[1, 0.5, 0.2]	[1, 0.5, 0.2]	334,476,967	5924	316,175,742	7597	323,020,947	311	316,578,694	11,000	2.165	2.035	5.788
			IC	1	0.4	0.1													

Table 8
Inventory policy variables in scenario 2 of Table 6.

Hub facility	Customers	\bar{S}_{ijkp}^t			\bar{S}_{ijkp}^{-t}			Shortage		
		$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$
Brownsville	17	15175.000 (Farmer 2)	0	0	0	8200.000 (Farmer 2)	6975.000 (Farmer 2)	0	0	0
Hub facility	Customers	\bar{S}_{ijkp}^t			\bar{S}_{ijkp}^{-t}			Shortage		
Havana	18	8010.375 (Farmer 1)	1200.000 (Farmer 2)	0	0	4847.559 (Farmer 1)	3162.816 (Farmer 1) +1200.000(Farmer 2)	0	0	0

Table 9
Inventory policy variables in scenario 2 of Table 6.

\bar{d}_{kl}^t	Customers	$t = 1$			$t = 2$			$t = 3$		
		Farmers			Farmers			Farmers		
		1	2	3	1	2	3	1	2	3
13	0	0	525.440	0	0	656.800	0	591.120	0	
14	0	1313.600	0	0	1642.000	0	0	1477.800	0	
15	0	0	2627.200	0	0	3284.000	0	540.295	2415.305	
16	0	0	1050.880	0	0	1313.600	0	1182.240	0	
17	0	0	5179.360	0	0	5.450	1905.090	0	124.815	
18	0	0	0	0	0	0	0	0	0	

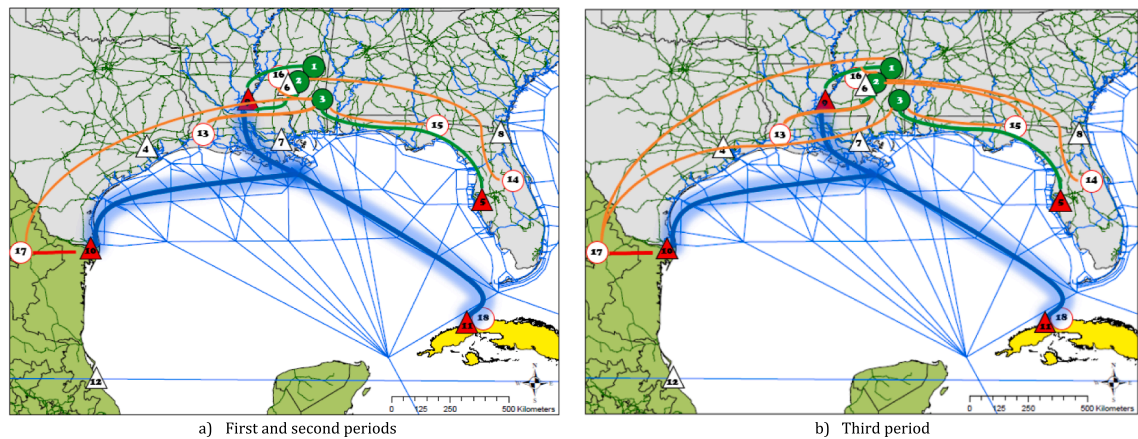


Fig. 7. Network configuration of scenario 2 in Table 7 for Model 2.

indirect logistics and under severe pandemic that limited available barges and did not have other option and consequently unsatisfaction of customers' demand was inevitable.

Fig. 8 indicates that for each level of access to barges, the direct distribution policy is more efficient than the indirect one. In this regard, the total amount of cost reduction due to direct distribution policy varies from 3% to 31%. The fewer barges (less than 15) and more direct the distribution will lead to more savings, because it is possible to reduce the volume of cargo transportation by sending goods directly by land. Under these conditions, when there are only 5 barges, the results show that the direct distribution method has cost saving up to 31.11%. Even when the number of barges is large enough, such as 20 barges, the direct distribution method would save 3.127%. This is due to the fact that it is not necessary to use waterways to transfer products between each farmer and the customers, especially for short distances or away from waterways. In these cases, the direct transfer of products to customers will reduce supply chain cost.

By performing sensitivity analysis, we can obtain that: 1) in all the scenarios, by increasing the minimum confidence of customer's demand satisfaction, the total cost of the poultry supply chain will be increased which means the proposed model is directly affected by uncertainty of customers' demand; 2) in all the scenarios, the implementation of the inventory policy in destination hubs will save the

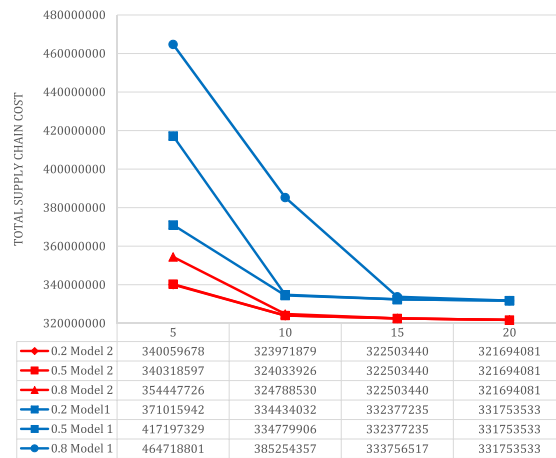


Fig. 8. Sensitive analysis on the maximum available of barges and parameter $\bar{\alpha}$.

Table 10

The values of customers' demand shortage for Model 1 and Model 2 when there are only 5 barges in the supply chain and $\bar{\alpha} \in \{0.2, 0.5, 0.8\}$.

Model type	Customers	$\bar{\alpha} = 0.2$			$\bar{\alpha} = 0.5$			$\bar{\alpha} = 0.8$		
		$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$	$t = 1$	$t = 2$	$t = 3$
Model 1	13	0.440	0	1.120	0.440	94.300	591.120	0.440	656.800	591.120
Model 1	14	0	0	2.800	13.600	4.500	1477.800	13.600	517.000	1477.800
Model 1	15	0	0	0.600	27.200	3046.500	2955.600	2127.200	3284.000	2955.600
Model 1	16	0	0	0.000	0.880	1.100	582.240	0.880	94.850	807.240
Model 1	17	0	0	7124.905	2979.360	10005.450	9004.905	2004.360	10005.450	9004.905
Model 1	18	0	0	4088.415	0	4225.599	4362.816	3878.040	4847.559	4362.816
Total		11218.280			39373.410			46629.660		
Model 2	13	0	0	0	0	0	0	0	0	0
Model 2	14	0	0	0	0	0	0	0	0	0
Model 2	15	0	0	0	0	0	0	0	0	0
Model 2	16	0	0	0	0	0	0	0	0	0
Model 2	17	0	0	0	0	0	0	0	0	4143.775
Model 2	18	0	625.599	4362.816	0	625.599	4362.816	0	1225.599	4362.816
Total		4988.415			4988.415			9732.190		

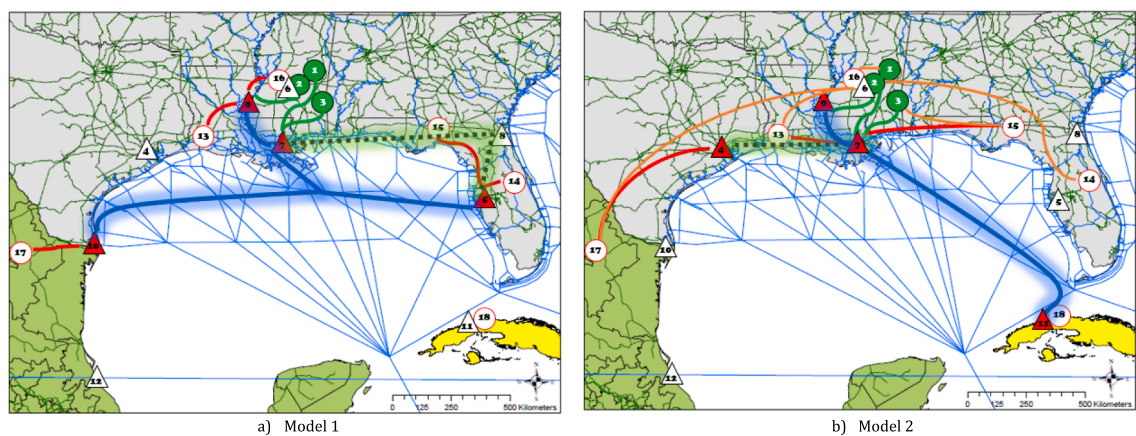


Fig. 9. Comparing network configuration of Model 1 and Model 2, when there are only 5 barges in the supply chain and $\bar{\alpha} = 0.8$

poultry supply chain cost during the pandemic peak; 3) in all scenarios, water transportation is preferable to rail transportation mode due to its high capacity, low cost, and easy accessibility for Mississippi farmers; and 4) during the peak of the pandemic, the land transport method is outperforming other transportation methods due to easier access.

6. Conclusion and future research

In this paper a mixed integer linear programming model was presented to study the effect of pandemic on a stochastic broiler supply chain in Mississippi State under seasonal variation and poultry diseases effect. In the first model (Model 1), farmers have access to an indirect logistic strategy under which products are distributed among domestic and international customers using either ship or rail transportation mode. In the second model (Model 2), farmers also can directly transport their products toward customers. To mitigate the negative effect of pandemic, in both models, farmers can stock their products in pre-pandemic period at destination hubs and distribute them among customers during the occurrence of pandemic, when not only production rate is being affected, but also access to mass transportation modes like ships and rails are restricted. To solve the models, a hybrid solution approach based on branch and cut and dynamic programming was developed. The obtained results indicated that the proposed stocking policy of farmers' productions during pre-pandemic effectively decreased the negative impact of pandemic on the economy of the broiler supply chain up 23.5539 %. This amount of cost savings can be increased up to 7.304% by using direct logistics alongside with multi-modal hub network. This is due to the fact that although mass transportation brings economy of scale, during pandemic accessing them is far difficult than direct logistic by truck. Therefore, counting only on multi-modal hub network cannot guarantee the optimality of product distribution policy. Furthermore, we examined the performance of proposed BBDP algorithm by comparing with CPLEX and CBC algorithms. The obtained results showed that BBDP's CPU time was up to 33 and 46 times faster than CPLEX in solving Model 1 and Model 2 with at most 1.868% and 4.515% gap, respectively. Also, BBDP was at least 43 and 33 times faster than CBC in solving Model 1 and Model 2 with at most 1.760% and 4.024% gap, respectively. The results of sensitivity analysis showed that for serving inter-hub paths, both models always prefer ship transportation mode than rail, due to its higher capacity, fewer transportation costs and using the capacity of Mississippi river waterway. When the number of barges is limited, Model 1 will be much more affected by the pandemic than Model 2 since it has only indirect logistics.

This study provides some applicable recommendations to the poultry industry to deal with the impacts of COVID 19. First and foremost, combining water transportation (which has high capacity and low operation cost) with stocking products during early stage of pandemic would enable farmers to store the products early and support them during peak of pandemic. Furthermore, it is better for transportation companies to use mass transportation system during non-pandemic period and land transportation (e.g., truck) during peak of pandemic. For the relevant food supply chains, such as pork and beef, the proposed model would bring some clues of how to manage producers' production, storage and distribute among customers to mitigate the risk during pandemic.

In this paper, only three major farmers and six customers in the Mississippi broiler supply chain were studied considering the computing capability limitations. Recognizing more farmers and customers may lead to more realistic outcomes. Moreover, this article did not address the unusual behaviors of customers during a pandemic, such as trying to abnormal store products or extreme changes in consumption patterns.

For future research we suggest extending this paper in the following directions. First, developing the broiler supply chain by studying the production process in detail. Focusing more on farmers' production processes will help them to better control production fluctuations caused by diseases or seasonal variations; furthermore, investigating the impact of agricultural associations in supporting farmers' production process during the pandemic period by centralized storage policy. A set of farmers acts as a major supplier that can cooperate together for supporting large areas; in addition, considering the effect of price fluctuation of services and raw materials during pandemic on different components of the broiler supply chain from the production process to the pattern of customer demand would make the results more realistic.

Declaration of Competing Interest

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

References

- Ala-Harja, H., Helo, P., 2014. Green supply chain decisions – Case-based performance analysis from the food industry. *Transport. Res. Part E: Logist. Transport. Rev.* 69, 97–107. <https://doi.org/10.1016/j.tre.2014.05.015>.
- Alizadeh, M., Ma, J., Marufuzzaman, M., Yu, F., 2019a. Sustainable olefin supply chain network design under seasonal feedstock supplies and uncertain carbon tax rate. *J. Cleaner Prod.* 222, 280–299.
- Alizadeh, M., Ma, J., Mahdavi-Amiri, N., Marufuzzaman, M., Jaradat, R., 2019b. A stochastic programming model for a capacitated location-allocation problem with heterogeneous demands. *Comput. Ind. Eng.* 137, 106055. <https://doi.org/10.1016/j.cie.2019.106055>.
- Amankwah-Amoah, J., 2020. Note: Mayday, Mayday, Mayday! Responding to environmental shocks: Insights on global airlines' responses to COVID-19. *Transport. Res. Part E: Logist. Transport. Rev.* 143, 102098. <https://doi.org/10.1016/j.tre.2020.102098>.
- Amin-Naseri, M.R., Yazdekhasti, A., Salmasia, A., 2018. Robust bi-objective optimization of uncapacitated single allocation p-hub median problem using a hybrid heuristic algorithm. *Neural Comput. Appl.* 29 (9), 511–532. <https://doi.org/10.1007/s00521-016-2520-4>.
- Amrani, S.E., Hossain, N.U.I., Karam, S., Jaradat, R., Nur, F., Hamilton, M.A., Ma, J., 2021. Modeling and assessing sustainability of a supply chain network leveraging multi Echelon Bayesian Network. *J. Cleaner Prod.* 302, 126855.
- Antipova, T., 2020. Coronavirus pandemic as Black swan event. *Integrated Sci. Digital Age* 2020, 356–366. https://doi.org/10.1007/978-3-030-49264-9_32.
- Aslam, H.B., Alarcon, P., Yaqub, T., Iqbal, M., Häsler, B., 2020. A value chain approach to characterize the chicken sub-sector in Pakistan. *Front. Veter. Sci.* 7 <https://doi.org/10.3389/fvets.2020.0036110.3389/fvets.2020.00361.s00110.3389/fvets.2020.00361.s002>.
- Austin, D., 2016. An analyst in CBO's Microeconomics Studies Division. Paper presented at the 91st Annual Conference of the Western Economic Association International.
- Balaman, Ş.Y., Selim, H., 2014. A network design model for biomass to energy supply chains with anaerobic digestion systems. *Appl. Energy* 130, 289–304. <https://doi.org/10.1016/j.apenergy.2014.05.043>.

- Barnes, B., Scott, A., Hernandez-Jover, M., Toribio, J., Moloney, B., Glass, K., 2019. Modelling high pathogenic avian influenza outbreaks in the commercial poultry industry. *Theor. Popul. Biol.* 126, 59–71. <https://doi.org/10.1016/j.tpb.2019.02.004>.
- Brevik, E., Lauen, A.Ø., Rolke, M.C.B., Fagerholt, K., Hansen, J.R., 2020. Optimisation of the broiler production supply chain. *Int. J. Prod. Res.* 58 (17), 5218–5237. <https://doi.org/10.1080/00207543.2020.1713415>.
- Chaudhry, M.I., Miranda, M.J., 2020. Price Transmission in Pakistan's Poultry Supply Chain. Retrieved from *J. Agric. Resour. Econom.* 45 (2), 282–298. http://ageconsearch.umn.edu/record/302455/files/JARE%2C45.2%2CMay2020.7%2CChaudhry%2C282-298w_Supplement.pdf. <https://doi.org/10.22004/agecon.302455>.
- Choi, T.-M., 2021. Risk analysis in logistics systems: A research agenda during and after the COVID-19 pandemic. *Transport. Res. Part E: Logist. Transport. Rev.* 145, 102190. <https://doi.org/10.1016/j.tre.2020.102190>.
- Chowdhury, E.U., Morey, A., 2019. Intelligent Packaging for Poultry Industry. *J. Appl. Poult. Res.* 28 (4), 791–800. <https://doi.org/10.3382/japr/pfz098> doi.
- Das, P.K., Samanta, I., 2021. Role of backyard poultry in south-east Asian countries: Post COVID-19 perspective. *World's Poult. Sci. J.* 77 (2), 415–426. <https://doi.org/10.1080/00439339.2021.1893620>.
- Duan, G., Aghalari, A., Chen, L., Marufuzzaman, M., Ma, J., 2021. Vessel routing optimization for floating macro-marine debris collection in the ocean considering dynamic velocity and direction. *Transport. Res. Part E: Logist. Transport. Rev.* 152, 102414.
- Esiogwu, A.C., Ejike, R.D., 2021. Effects of COVID-19 on poultry production in south-east agro-ecological zone of Nigeria. *Nigerian J. Anim. Prod.* 48 (4), 253–261. <https://doi.org/10.51791/njap.v48i4.3003>.
- Ghozzi, H., Soregaroli, C., Boccaletti, S., Sauvé, L., 2016. Impacts of non-GMO standards on poultry supply chain governance: transaction cost approach vs resource-based view. *Supply Chain Manage.: Int. J.* 21 (6), 743–758. <https://doi.org/10.1108/SCM-03-2016-0089>.
- Gital Durmaz, Y., Bilgen, B., 2020. Multi-objective optimization of sustainable biomass supply chain network design. *Appl. Energy* 272, 115259. <https://doi.org/10.1016/j.apenergy.2020.115259>.
- Govindan, K., Mina, H., Alavi, B., 2020. A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19). *Transport. Res. Part E: Logist. Transport. Rev.* 138, 101967. <https://doi.org/10.1016/j.tre.2020.101967>.
- Hafez, H.M., Attia, Y.A., 2020. Challenges to the poultry industry: Current perspectives and strategic future after the COVID-19 outbreak. *Front. Veter. Sci.* 7 <https://doi.org/10.3389/fvets.2020.00516>.
- Ritchie, H., Roser, M., 2017. August. *Meat and dairy production*. Our World in Data.
- Ivanov, D., 2020. Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transport. Res. Part E: Logist. Transport. Rev.* 136, 101922. <https://doi.org/10.1016/j.tre.2020.101922>.
- Kalhor, T., Rajabipour, A., Akram, A., Sharifi, M., 2016. Environmental impact assessment of chicken meat production using life cycle assessment. *Inform. Process. Agric.* 3 (4), 262–271. <https://doi.org/10.1016/j.inpa.2016.10.002>.
- Kolluri, G., Tyagi, J.S., Sasidhar, P.V.K., 2021. Research note: Indian poultry industry vis-à-vis coronavirus disease 2019: a situation analysis report. *Poult. Sci.* 100 (3), 100828. <https://doi.org/10.1016/j.psj.2020.11.011>.
- Le Hoa Vo, T., Thiel, D., 2011. Economic simulation of a poultry supply chain facing a sanitary crisis. *British Food J.* 113 (8), 1011–1030. <https://doi.org/10.1108/0007071111153760>.
- Maples, J. G., Thompson, J. M., Anderson, J. D., & Anderson, D. P. (2020). Estimating COVID-19 Impacts on the Broiler Industry. *Applied Economic Perspectives and Policy*, n/a(n/a). doi:<https://doi.org/10.1002/aep.13089>.
- Maslova, G. M., Glinkina, I. M., Kashirina, N. A., & Bailova, N. V. (2020, 2020/07/30). Market Research of the Egg Food Market. Paper presented at the International Conference on Policies and Economics Measures for Agricultural Development (AgroDevEco 2020).
- Mogale, D.G., Kumar, M., Kumar, S.K., Tiwari, M.K., 2018. Grain silo location-allocation problem with dwell time for optimization of food grain supply chain network. *Transport. Res. Part E: Logist. Transport. Rev.* 111, 40–69. <https://doi.org/10.1016/j.tre.2018.01.004>.
- Palouj, M., Lavaei Adaryani, R., Alambeigi, A., Movarej, M., Safi Sis, Y., 2021. Surveying the impact of the coronavirus (COVID-19) on the poultry supply chain: A mixed methods study. *Food Control* 126, 108084. <https://doi.org/10.1016/j.foodcont.2021.108084>.
- Park, K., Okudan Kremer, G.E., Ma, J., 2018. A regional information based multi-attribute and multi-objective decision-making approach for sustainable supplier selection and order allocation. *J. Cleaner Prod.* 187, 590–604.
- Parvin, R., Begum, J.A., Nooruzzaman, M., Chowdhury, E.H., Islam, M.R., Vahlenkamp, T.W., 2018. Review analysis and impact of Co-circulating H5N1 and H9N2 avian influenza viruses in Bangladesh. *Epidemiol. Infect.* 146 (10), 1259–1266. <https://doi.org/10.1017/S0950268818001292>.
- Patra, M.K., Hajra, D., Das, R., Sarkar, P., Deka, B., 2017. Effect of season on growth and reproduction performance of improved backyard poultry in North Eastern Hill Region. *Indian J. Anim. Res.* <https://doi.org/10.18805/ijar.v010IF.9156>.
- Railroads Shapefiles/NA_Railroads/data/rail1/railroads_1_v2.zip, North America Railroads, [ciecebase.gov/catalog/item/4fb5b74e4b04cb937751de9](https://catalog.item/4fb5b74e4b04cb937751de9), 2.171.0, 2020.
- Sebatjane, Makoena, Adetunji, Olufemi, 2020. A three-echelon supply chain for economic growing quantity model with price- and freshness-dependent demand: Pricing, ordering and shipment decisions. *Oper. Res. Perspect.* 7, 100153. <https://doi.org/10.1016/j.orp.2020.100153>.
- Serper, E.Z., Alumur, S.A., 2016. The design of capacitated intermodal hub networks with different vehicle types. *Transport. Res. Part B: Methodolog.* 86, 51–65. <https://doi.org/10.1016/j.trb.2016.01.011>.
- Singh, Sube, Kumar, Ramesh, Panchal, Rohit, Tiwari, Manoj Kumar, 2021. Impact of COVID-19 on logistics systems and disruptions in food supply chain. *Int. J. Prod. Res.* 59 (7), 1993–2008. <https://doi.org/10.1080/00207543.2020.1792000>.
- Tsolakis, N., Srai, J.S., Aivazidou, E., 2018. Blue Water Footprint Management in a UK Poultry Supply Chain under Environmental Regulatory Constraints. *Sustainability* 10 (3), 625.
- Unveren, H., Luckstead, J., 2020. Comprehensive Broiler Supply Chain Model with Vertical and Horizontal Linkages: Impact of US–China Trade War and USMCA. *J. Agric. Appl. Econ.* 52 (3), 368–384. <https://doi.org/10.1017/aae.2020.5>.
- Uyanga, Victoria A., Onagbesan, Okanlawon M., Onwuka, C.F.I., Emmanuel, Babajide, Lin, Hai, 2021. Coronavirus disease 2019 (COVID-19) and poultry production: Emerging issues in African countries. *World's Poult. Sci. J.* 77 (1), 153–174. <https://doi.org/10.1080/00439339.2021.1874848>.
- Wagner, H.M., Whitin, T.M., 1958. Dynamic Version of the Economic Lot Size Model. *Manage. Sci.* 5 (1), 89–96. <https://doi.org/10.1287/mnsc.5.1.89>.
- Weersink, Alfons, Massow, Mike, McDougall, Brendan, 2020. Economic thoughts on the potential implications of COVID-19 on the Canadian dairy and poultry sectors. *Can. J. Agric. Econom./Revue canadienne d'agroeconomie* 68 (2), 195–200. <https://doi.org/10.1111/cjag.v68.210.1111/cjag.12240>.
- World Bank, 2005. Spread of Avian Flu Could Affect Next Year's Economic Outlook. In: Bank, World (Ed.), *East Asia Update – Countering Global Shocks*. USA, World Bank Press, Washington D.C.
- Wu, Jian-Yong, Lau, Eric HY, Yuan, Jun, Lu, Ming-Ling, Xie, Chao-Jun, Li, Kui-Biao, Ma, Xiao-Wei, Chen, Jian-Dong, Liu, Yan-Hui, Cao, Lan, Li, Mei-Xia, Di, Biao, Liu, Yu-Fei, Lu, Jian-Yun, Li, Tie-Gang, Xiao, Xin-Cai, Wang, Da-Hu, Yang, Zhi-Cong, Lu, Jia-Hai, 2019. Transmission risk of avian influenza virus along poultry supply chains in Guangdong China. *J. Infect.* 79 (1), 43–48. <https://doi.org/10.1016/j.jinf.2019.05.006>.
- Xiao, X., Wang, W., Zhang, X., Zhang, J., Liao, M., Yang, H., Li, Y., 2019. Modeling the Reduction of Salmonella spp. on Chicken Breasts and Wingettes during Scalding for QMRA of the Poultry Supply Chain in China. *Microorganisms* 7 (6), 165.
- Young, K., R.I. Carreira, H.L. Goodwin, and E. Wailes. (2005). Economics of Transporting Poultry Litter from Northwest Arkansas to Eastern Arkansas Croplands. Selected paper at the Southern Agricultural Economics Association annual meetings, Little Rock, AR. Available at <http://ageconsearch.umn.edu/bitstream/35635/1/sp05yo01.pdf> (accessed November 26, 2020).