Study on The Supply Security of Fresh Products Under Public Health Emergencies

Yi Lu[1,*], *Lu* Yu[1], *Yutong* Gan[1], and *Valerie Lynette* Wang[2]

[1]Institute of Emergency Management, Sichuan University, Chengdu, People's Republic of China
[2]College of Business and Public Management West Chester University West Chester, Pennsylvania 19383, USA

Abstract. Strict control taken in response to public health emergencies (PHEs) can hinder fresh products supply, while stock-outs and the risk of epidemics can increase fresh products demand. To explore the interrelationship between outbreak control measures and the availability of fresh products, this paper establishes a dynamic synergistic model of epidemic transmission subsystem and fresh products supply-consumption subsystem based on system dynamics (SD). Taking the spread of COVID-19 in Shanghai from March to May 2022 as the actual background, the impact of different storage strategies and control measures on epidemic prevention and material supply was quantitatively evaluated. The results show that risk transmission factor (RTF) affects the number of infections and the intensity of community control contributes to controlling the spread of the epidemic, but it can continue to affect fresh product supply security. Therefore, increasing fresh product protection inputs and reducing in-transit time can reduce fresh product losses and improve fresh product supply security under PHEs. The findings can enable fresh products to effectively match supply and demand under PHEs, mitigate the impact of epidemic risks and provide decision support for relevant retailers. **Keywords:** Supply chain, Fresh products, COVID-19, System dynamics.

1 Introduction

Epidemic outbreaks are a kind of fresh product supply chain risks which is distinctively characterized by a long-term disruption existence, disruption propagations, and high uncertainty [1]. During the spread of an epidemic, fresh products are often out of stock due to epidemic control measures and imbalances in supply and demand, leading to a failure of market mechanisms and exceptionally high fresh product prices [2]. The supply of fresh product in the event of a major PHE has become a hot issue of concern to government departments, researchers and the public. Therefore, analyzing the relationship between epidemic risk transmission and fresh products supply chain to mitigate the impact of epidemic risks is of vital importance.

Research on emergency supply chain management is relatively well established. Nartey et al. [3] proposed a fuzzy emergency model and a robust emergency strategy of the supply chain system for random distributors under supply disruptions caused by emergency incidents. Thomas and Mahanty [4] presented a dynamic simulation approach for analyzing the

*e-mail: luyiscu@scu.edu.cn

well-known emergency sourcing mitigation strategy for a supply chain subject to disruption of its primary supply. A closed-loop supply chain material flow and capital flow coupling system composed of manufacturers, sellers and recyclers was constructed by Duan et al. [5] to explore the impact of material flow sudden interruption on the closed-loop supply chain system when an uncertain emergency occurs. Ivanov [6] predicted the impacts of epidemic outbreaks on global supply chains by a simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. Richards [7] analyzed the Canadian fruit and vegetable markets impacted by COVID-19 disease, and Wu [8] studied the time-dependent split delivery green vehicle routing problem with multiple time windows by designing a calculation method for road travel time across time periods. The limitation of the above studies is that they mainly focus on the transmission mechanism of epidemic, emergency strategy and fresh products distribution, but rare article has analyzed the interrelationship between various factors from the perspective of the system synergy between epidemic risk transmission and fresh products supply. This paper analyzes the relationship between epidemic risk transmission and fresh products supply chain based on the SD theory, and the findings can enable fresh products to effectively match supply and demand under PHEs, mitigate the impact of epidemic risks and provide decision support for relevant retailers.

This study is organized as follows. Section 1 reviews the literature regarding the analysis of fresh products emergency supply chain management. Section 2 introduces the model description and causality. Section 3 presents the assumptions and Variable Settings. Section 4 presents a case study and experimental results. The paper concludes by summarizing the research findings in Section 5.

2 Model Description and Causality

2.1 Analysis of Fresh Product Supply and Demand Under PHEs

This paper constructs a dynamic model of fresh products supply-consumption in PHEs around the change of epidemic risk and fresh products spoilage rate, and defines the scope of the model as the epidemic transmission subsystem and fresh products supply-consumption subsystem. These two subsystems operate dynamically through the interaction of endogenous and exogenous factors.

Through the epidemic transmission subsystem, the development trend of the epidemic can be described and the number of infections in the region can be dynamically predicted. The dynamic changes of the epidemic development can then be used to formulate control policies, including traffic control policies, community control policies and fresh products deployment policies, etc. Through the fresh products supply-consumption subsystem, the dynamic changes of demand and supply of fresh products under different stages can be portrayed. Drawing on the successful experience of commercial logistics, the supply chain of disaster relief materials can be regarded as a complete chain covering the acquisition, storage, distribution and transportation of relief materials from the supply side to the disaster area [9]. It can be concluded that the supply of fresh products under PHEs includes three sources, which are pre-disaster strategic reserves, regional production under PHEs, and assistance from other regions of society. Unlike the material consumption in the commercial environment, the material consumption of fresh products under PHEs discussed in this paper is characterized by strong uncertainty and volatility [10]. The consumer demand for fresh products varies during the different phases of a PHE. As an epidemic develops, demand for fresh products fluctuates with changes in regional population, epidemic control measures and risk awareness. Therefore, the quantity of fresh products deteriorated is determined by the rate of deterioration, transportation time and deployment time. In summary, the flow of supply and demand for fresh products under PHEs is shown in figure 1. In this paper, Vensim is used to support the analysis and study of different systems.

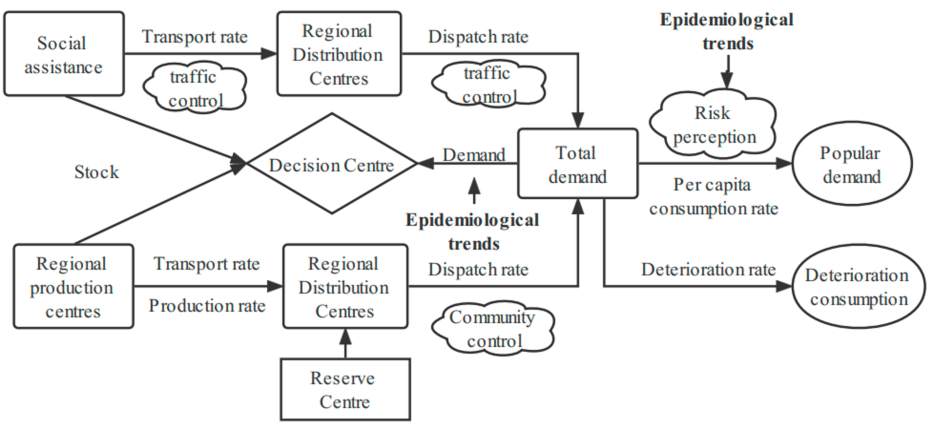

Figure 1. Supply-demand operation process of fresh products

2.2 Causality Analysis

(1) Epidemic transmission subsystem

In the epidemic transmission subsystem, the transmission mechanism of Covid-19 is analyzed based on the disease transmission dynamic theory [11] and a multi-compartment transmission dynamic model is established combining Chinese government's response strategy and specific control measures for the Covid-19. As the outbreak spreads, the number of infected people increases, which makes the susceptible population infected and transform into latent patients. In this subsystem, the causal circuit diagram is shown in figure 2. Under positive feedback regulation, if no intervention is taken, the epidemic will spread widely and cause the subsystem to collapse. Therefore, the intervention of government departments is needed to give external intervention to interrupt the spread of the epidemic.

(2) Fresh products supply-consumption subsystem

Combined with the demand supply characteristics of fresh products supplies under PHEs, this paper analyzes the feedback and causality of the subsystem based on the Sterman's [12, 13] general inventory management model and construct a SD model of fresh products supply-consumption.

In the early stages of epidemic, the deployment of fresh products is determined by the distribution center, whose supplies come from strategic reserve center inventory, local production and external assistance, regulated by expected inventory, production delays and transport time delays. The cause and effect loop diagram is shown in figure 3. Under negative feedback regulation, attention should be paid to the regulation of inventory to improve the supply security rate of fresh products. At the same time, attention should be paid to reducing transport time and deployment time to minimize the loss of fresh products due to spoilage. The intervention of policy makers is therefore needed to rationalize the supply of fresh agricultural products.

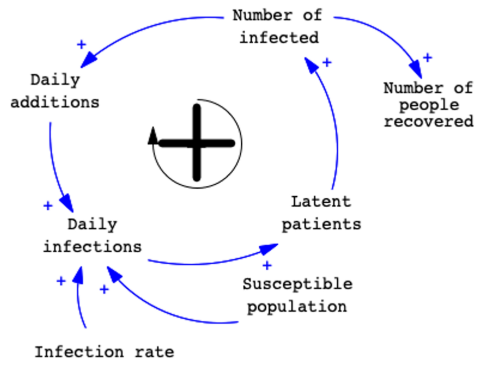

Figure 2. Causal loop diagram of the epidemic transmission subsystem

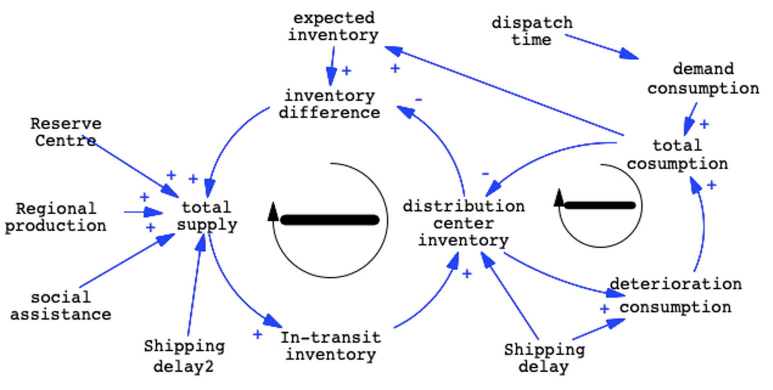

Figure 3. Causal loop diagram of the fresh products supply-consumption subsystem

3 Model

3.1 Assumptions and Variable Settings

(1) Assumption

Based on the scope and content of the model, this paper made the following assumptions.

Hypothesis 1. Under PHEs, the distribution of fresh products is carried out uniformly in distribution centers.

Hypothesis 2. People and decision makers can access the number of infected people and perceive the risk situation in real time through platforms such as the Internet, and propose changes in the demand for fresh products based on risk perception.

Hypothesis 3. Regional reserves and local production are not enough to meet people's demand for fresh products consumption during under PHEs, so assistance is needed from outside; there will be a time delay for fresh products to reach the demanders, so there will also be goods loss due to deterioration, and the rate of goods loss and deterioration is proportional to the delay time and preservation of fresh inputs. It can be expressed in Eq. (1).

$$\theta = a + \frac{bt_{delay}}{p_{input}}(a > 0, b > 0). \tag{1}$$

Hypothesis 4. The mobile population within the region is not considered to change over time, and the cured patients will not be re-infected; the treatment period of patients is fixed.

Hypothesis 5. Safety stock I_E is a good solution for shipping delays and abnormal demand amplification, while also ensuring a high inventory service level. The service level is typically set at 95%. It can be expressed in Eq. (2).

$$I_E = z \times \sigma \sqrt{LT}. \tag{2}$$

Set the lead time to 1 day and the initial safety stock to I_E .

Hypothesis 6. The epidemic risk transmission comes from the number of patients, and this paper uses Eq. (3) to describe the epidemic RTF.

$$r_f = \log\left(Max\left(1, I\right), 10\right). \tag{3}$$

(2) Variable settings

The main parameters and variables are set as table 1:

Table 1. Parameters and Variables

Sign	Definition	Sign	Definition	Sign	Definition	Sign	Definition
N	Total number	S	Susceptible persons	I	Infected	E	Latent patients
R	Recovered	a	Isolation rate	c	Recovery rate	t_1	Shipping delay
INF	Infection rate	β	Number of infections	DUR	Recovery period	t_2	Dispatch time
γ	Number of recoveries	p	Number of contacts	r_f	RTF	t_3	Production delay
T	Infection periods	σ	Transforming person	r_P	Risk perceptions	t_4	Measure delay
t	Transforming rate	Tss	Transition period	e	Frequency of effective exposure	t_5	Shipping delays1
I_j	Distribution center inventory	s_1	External assistance arrivals	ε	External assistance fulfilment rate	t_6	Delayed delivery
I_t	In-transit inventory	s_2	External demand	ε_1	Production efficiency	t_7	Delayed demand consumption
I_c	Inventory difference	s_3	Regional production	r_t	Traffic transfer intensity	t_8	Control delay
I_e	Expected inventory	s_4	Initial production capacity	r_s	Regional control intensity	θ	Fresh products spoilage rate
Is	Reserve center reserves	S_5	Post-production capacity	η	Material availability	t_{11}	Delayed implementation of preventive measures
Dp	Daily per demand	L_1	Initial logistics transport capacity	d	Decision preferences	t_i	Information delay
DA	Daily Area demand	L_2	Daily transport capacity	q_3	Arrival quantity	q_4	Deterioration rate
q_1	Shipment	q_2	Total shipment	q_5	Demand consumption	P	Preservation input

3.2 Stock and Flow Diagram

This paper uses SD principles to construct a model about the epidemic transmission subsystem and the fresh products supply-consumption subsystem. Based on the causal analysis in Section. 2, a stock and flow diagram is drawn up, as shown in figure 4.

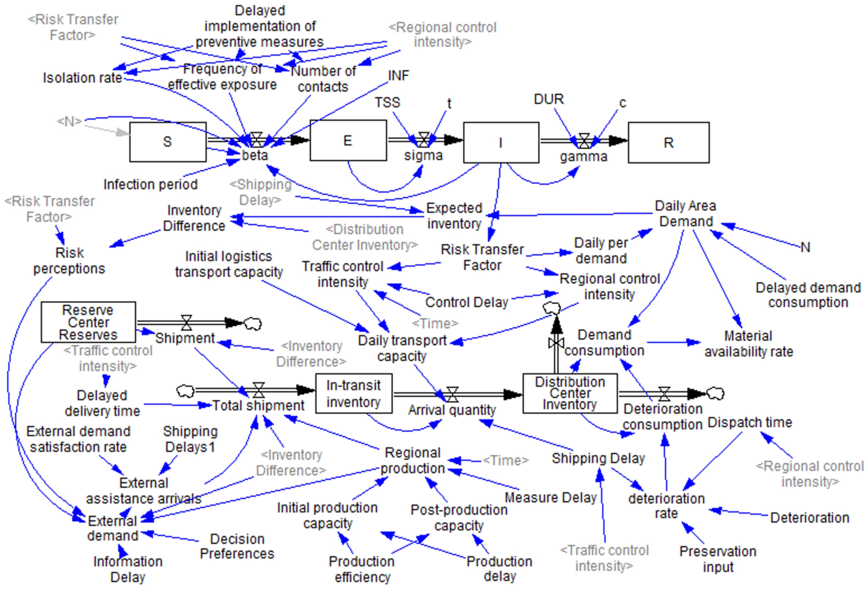

Figure 4. The stock and flow diagram of the system

3.3 System Equations

(1) Epidemic transmission subsystem

Considering the basic pattern of the virus from infection to disease, this paper expands based on the SEIR model and classifies infected persons as latent infected persons (E) and infected(I), which is more consistent with the transmission pattern of this COVID-19 outbreak [14]. Infection from susceptible to latent is determined by the transmission rate, average number of contacts, frequency of contacts, the proportion of infected and the transmission cycle; conversion of latent to infected is related to the conversion rate and the incubation period; recovery from infected to non-infected is determined by the recovery rate and the treatment cycle.

Eq. (4) describes the process of susceptible individuals being infected by the virus:

$$\frac{\mathrm{d}E}{dt} = -S\beta I\frac{1-\alpha}{N}. \tag{4}$$

Eq. (5) describes the transformation of latent patients into infected patients:

$$\frac{\mathrm{d}I}{dt} = S\beta ep\frac{1-\alpha}{N} - \frac{Et}{TSS}. \tag{5}$$

Eq. (6) describes the process by which an infected person heals or dies after a period of time:

$$\frac{\mathrm{d}R}{dt} = \frac{Et}{Tss} - \frac{Ic}{DUR}. \tag{6}$$

The epidemic RTF is set to describe the development of the COVID-19 epidemic, and Eq. (7) describes the evolution of the RTF with the number of infections in the development of the epidemic:

$$r_f = LOG\left(MAX\left(1, I\right), 10\right). \tag{7}$$

(2) Fresh products supply-consumption subsystem

On the demand side, the risk of an epidemic has increased market demand. On the supply side, the production, stocking and outward transfer of supplies are affected by the government [15]. The subsystem is described as follows:

Eq. (8) describes changes in strategic center reserves, the strategic center serves as a quantitative reserve of regional emergency supplies.

$$\frac{\mathrm{d}I_s}{dt_5} = -q_1. \tag{8}$$

The supply of fresh products is the total of strategic reserve center inventory, local production and external aid arrivals, and shipments of fresh products q_2 is adjusted by the inventory difference. Eq. (9) describes the shipments of fresh products q_2.

$$q_2 = \begin{cases} q_1 + S_1 + S_3, I_c > 0. \\ 0, I_c > 0. \end{cases} \tag{9}$$

In-transit inventory is introduced to describe the amount of inventory that has been shipped but has not yet arrived at the distribution center. Eq. (10) describes the evolution of in-transit inventory levels.

$$\frac{\mathrm{d}I_t}{dt_1} = q_2 - q_3. \tag{10}$$

Arrival volume q_3 is determined by daily regional transportation capacity and in-transit inventory, Eq. (11) describes the change in arrivals.

$$q_2 = Min\left(\frac{I_t}{t_1}, L_2\right). \tag{11}$$

Eq. (12) describe the changes in inventory levels in the distribution center.

$$\frac{\mathrm{d}I_J}{dt_1} = q_3 - q_4 - q_5. \tag{12}$$

Eq. (13) describes changes in the amount of demand consumption of fresh products. Eq. (14) describes the amount of spoilage loss of fresh products.

$$q_5 = Min(D_A, I_j - q_4). \tag{13}$$

$$q_4 = \theta * \frac{I_J}{t_2}. \tag{14}$$

Eq. (15) describes the relationship between the intensity of traffic control and the RTF; Eq. (16) describes the relationship between community control intensity and RTFs.

$$r_t = \begin{cases} \max(r_f - 1, 0), time \leq 30. \\ \max(r_f - 2, 0), time > 30. \end{cases} \tag{15}$$

$$r_s = \min(r_f - 1, 3). \tag{16}$$

4 Application

4.1 Data

The initial data for this paper was obtained from the National Statistics Office's population and industry statistics reports, some of which were collated from the reports, and the simulation model was operated for a length of 70 days in days, with a start date of 1 March 2022. Variables in the two subsystems are listed in table 2 and table 3.

Table 2. Infectious Disease Subsystem

Variables/unit	value	Variables/unit	value
$N/(hundred)$	2400	t_{11}	5
$T\,(day)$	$RANDOMNORMAL(3,7,5,1,3)$	INF	$RANDOMNORMAL(0.1,0.25,0.16,2,0.15)$
TSS	3	DUR	15
t	0.08	c	0.08
e	(2, 12)	P	(1, 6)

Table 3. Fresh products supply-consumption subsystem

Variables/unit	value	Variables/unit	value
Is	80000000	ε	0.6
L_1	37500000	S_4	DELAY1(ε_1,t$_3$)
t_6	$(0.2, 0.5)$	S_5	DELAY1(ε_1+1500,t$_3$)
t_1	$(0.5, 2)$	s_1	2000
t_8	0.5	t_1	1
t_7	1	t_2	$(0.1, 0.25)$
D_p	0.3	t_5	$(2, 4)$

4.2 Model Reality Check

Relying on the data released by the Shanghai Health Care Commission, the number of COVID-19 infections in Shanghai from March 1 to May 31, 2022 is obtained. Based on the data settings of the epidemic transmission subsystem in Section 4.1, the simulated number of infections can be derived by running the simulation program, as shown in figure 5. It can be seen that the curves for the simulated and real values fit well, with both curves peaking near day 45 (15 April 2022), and they maintain the same increasing and decreasing trend around the peak.

On the fresh products supply side, figure 6 shows the changes in the supply, in-transit inventory and consumption of fresh agricultural products. In the early stage, demand consumption was satisfied to a high degree due to the stockpile in the regional reserve centre and the incubation period of the epidemic; in the later stage, when the amount of external aid was needed to meet people's demand, both supply and consumption declined under the oversupply situation, which was in line with the actual situation. Therefore, the simulation model in this paper is able to reflect the spread of virus infection and the supply-consumption of fresh agricultural products in Shanghai to a certain extent.

4.3 Sensitivity analysis

To assess the impact of different levels of RTF, control measures and timeliness of fresh agricultural products on epidemic development and the fresh product supply chain, the following sensitivity analyses were conducted.

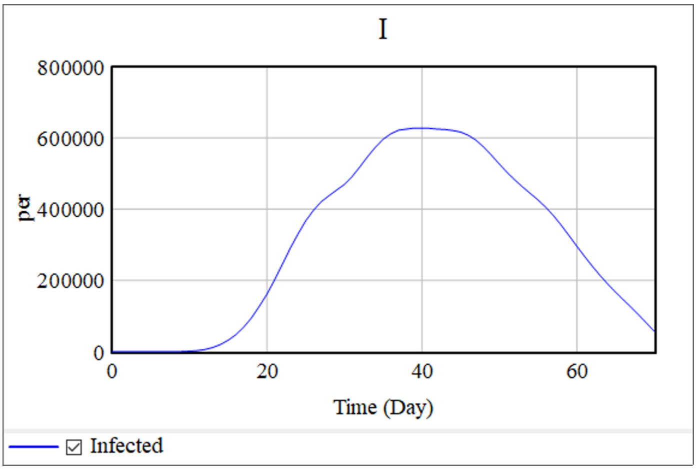

Figure 5. Number of Omicron infections in Shanghai

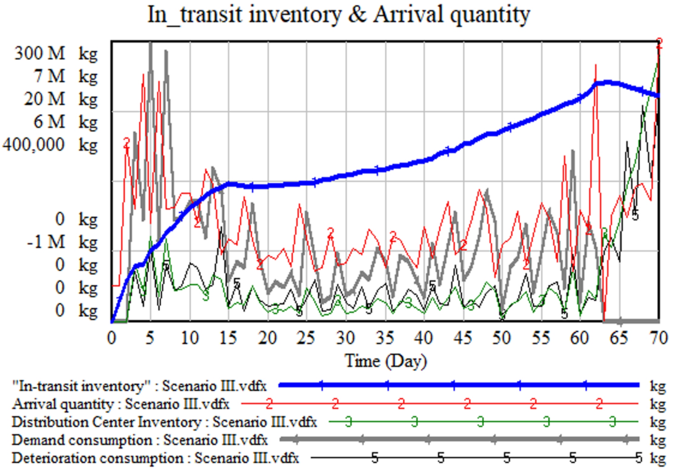

Figure 6. Fresh products supply chain

(1) RTF

The most direct reference for the public and policy makers to determine the risk of the epidemic is the number of new infections and the cumulative number of infections. Therefore, this paper introduces RTF to quantify the risk caused by the change in the number of infections, and the relationship between the two is shown in Eq. (17). This section sets the epidemic development and fresh products supply security under the following RTF settings with risk transmission capacity of 1, 0.5, and 1.3 levels. In figure 7, for epidemic transmission, the stronger the risk transmission capacity, the lower the cumulative number of infections; for raw material supply trumpets, the stronger the risk transmission capacity, the higher the amount of external aid arrives after depleting local inventory, but the lower the stock in the distribution center, the lower the population supply security rate.

$$
r_f = \begin{cases} 0, 0 \leq I \leq 10. \\ 1, 11 \leq I \leq 100. \\ 2, 101 \leq I \leq 1000. \\ 3, 1001 \leq I \leq 10000. \\ 4, 10001 \leq I \leq 100000. \\ 5, 100001 \leq I \leq 1000000. \\ 6, I > 1000000. \end{cases} \tag{17}
$$

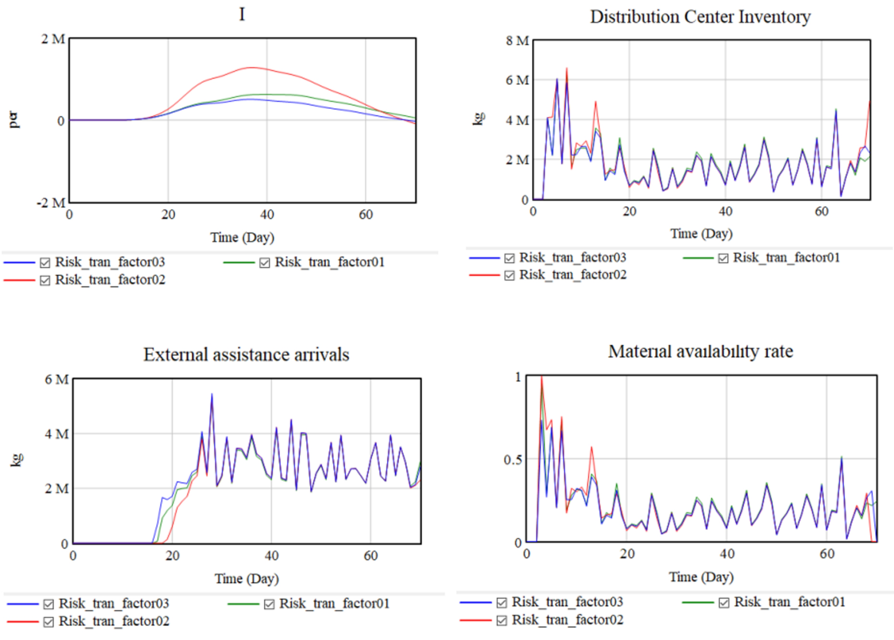

Figure 7. Risk transmission capacity change impacts

(2) Control intensity impact factor

Temporary control is a series of restrictive measures formulated by regional decision makers. In this paper, traffic control intensity and community control intensity are introduced to measure the change of control intensity, and the relationship between epidemic RTFs and two types of control intensity is seen as Eq. (18-19). The intensity of traffic control affects the logistics and timeliness of fresh products, and the intensity of community control affects the number of people infected by the virus. The following control intensity settings shown in table 4 explore the impact of control intensity on the development of the epidemic and the supply of fresh products. As shown in figure 8, Scenario 3 (traffic control relaxed after 40 days of outbreak development and community control 1.2 times normal) as the strictest control measures can significantly reduce the number of infections, but also affects the logistics of fresh supplies, resulting in low stock levels in the distribution centers and the lowest rate of population demand satisfaction.

$$
r_t = \mathrm{SMOOTH}(\mathrm{IFTHENELSE}(\mathrm{Time} >= 30, \mathrm{MAX}(r_f - 3, 0), \mathrm{MAX}(r_f - 1, 0)), t_8). \tag{18}
$$

$$r_s = \text{SMOOTH}(\text{IFTHENELSE}(r_f - 3 >= 0, \text{MIN}(r_f - 1, 3), 0), t_8). \tag{19}$$

Table 4. Fresh products spoilage rate factor

	Scenario I	Scenario II	Scenario III
Control intensity 1	$(r_t : Time \geq 30, r_s)$		
Control intensity 2		$(r_t : Time \geq 15, 0.8 * r_s)$	
Control intensity 3			$(r_t : Time \geq 40, 1.2 * r_s)$

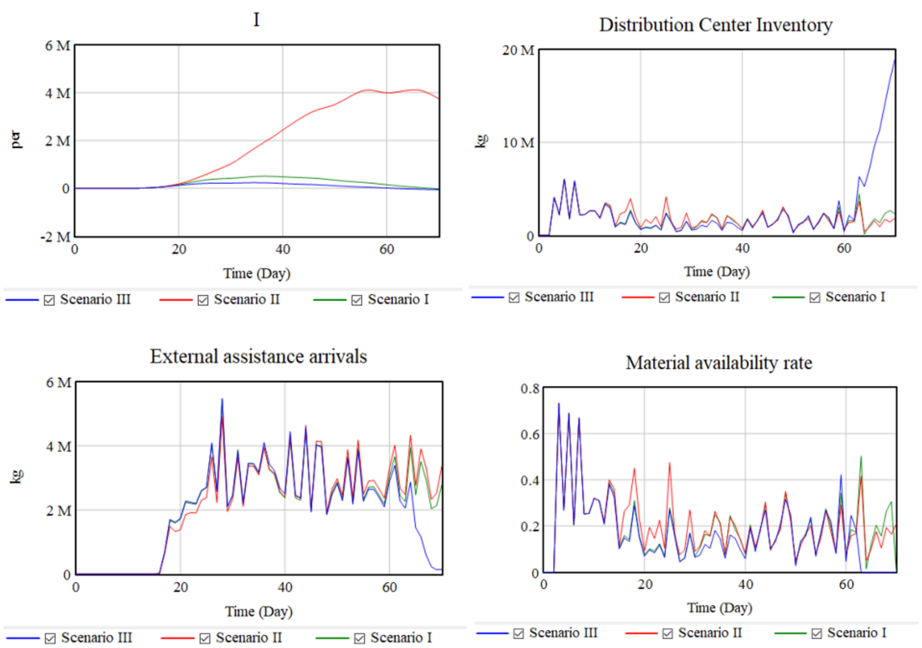

Figure 8. Risk transmission capacity change impacts

(3) Fresh products spoilage rate factor

As a necessity, the deterioration rate of fresh products can affect the inventory consumption of distribution centers. In case of emergency, the supply of fresh products is already less than the demand, and the consumption of deterioration makes it impossible to meet the demand of the people. On the one hand, the deterioration rate is influenced by the in-transit time and distribution time, on the other influenced by the characteristics of the material itself. This section introduces the relationship between deterioration rate and time and preservation input to explore the relationship between deterioration and supply satisfaction rate. Three scenarios in table 5 are set up for simulation, the results are shown in figure 9. The larger the deterioration factor, the smaller the freshness preservation input, and the more obvious the deterioration consumption, the weaker the freshness supply guarantee ability.

5 Conclusion

Under PHEs, controlling the spread of the epidemic and securing the supply of fresh products is a major challenge. This research gives a reasonable forecast of the epidemic development

Table 5. Fresh products spoilage rate factor

	Preservation & Time0	Preservation & Time1	Preservation & Time2
Deterioration rate 1	$a = 0.01; p = 1$		
Deterioration rate 2		$a = 0.05; p = 0.8$	
Deterioration rate 3			$a = 0.005; p = 1.2$

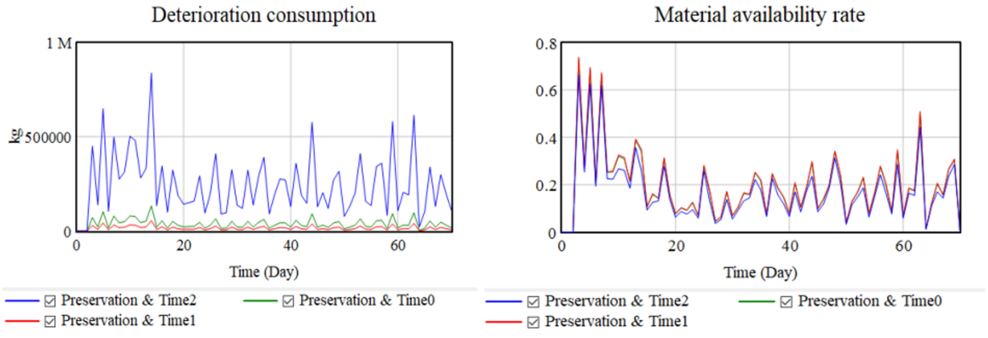

Figure 9. Fresh products deterioration rate factor

trend and the dynamic consumption progress of fresh products supply, which provides decision support to control the spread of the epidemic, and gives an optimization idea for reducing the consumption of deterioration fresh products and improving the security rate of people's demand under the situation that the supply of fresh products exceeds the demand. In the epidemic transmission subsystem, this paper uses infected people as the measurement object to explore the impact of RTFs and social control intensity on the dynamic changes of epidemic development; in the fresh products supply-consumption subsystem, spoilage rate is used to study the dynamic changes of external aid, distribution center inventory, demand consumption, spoilage consumption and material security rate. By combining the development of an epidemic with the process of securing the supply of fresh products, this paper extends the traditional SD model to achieve an assessment of the impact of different epidemic prevention measures on the securing of the supply of fresh products.

This study found that: (1) The RTF has a strong impact on the development of the epidemic. As the RTF grows, the cumulative number of infections decreases significantly, but the corresponding fresh products supply assurance rate also decrease, so it is necessary to reasonably disseminate the development dynamics of the epidemic and control the risk factor of the epidemic. (2) Epidemic prevention and control measures can effectively inhibit the spread of the virus, and the community control measures have the most obvious effect on the cumulative number of infections, the weaker community control intensity, the significantly higher the number of infections; On the other hand, the adjustment time of traffic control intensity has an impact on the delivery and supply security of fresh products; the faster the adjustment of traffic control intensity, the higher the supply security rate. (3) Controlling the deterioration rate of fresh products is an effective measure to alleviate the insufficient supply of fresh products during PHEs. On the one hand, speeding up the circulation of materials and reducing transportation time can help reduce the deterioration rate.

The limitations of this paper are as follows: (1) Due to the difficulty of obtaining data from the districts and counties, there is no detailed analysis of the supply and demand security of fresh supplies under PHEs in each district in Shanghai. Further consideration can be given to the relationship between the deployment of fresh supplies in different regions and the development of the epidemic, and diversified research can be conducted on the deployment methods, such as the introduction of non-ground transportation drones can greatly reduce the transportation time and is not affected by traffic control measures. (2) There should be more connecting factors between the epidemic transmission subsystem and the fresh products supply-consumption subsystem, and the introduction of changes in labor force, rapid growing techniques for fresh products, etc. could be considered in the future. An extended model based on the SD model in this paper can be constructed to continue exploring the above two aspects.

This research was supported by the Major Bidding Program of National Social Science Foundation of China (No. 22&ZD142), and the Research Funding of Sichuan University (2020skjd-py04)

References

[1] M.M. Queiroz, D. Ivanov, A. Dolgui, S. Fosso Wamba, Annals of operations research **319**, 1159 (2022)
[2] M. Çakır, Q. Li, X. Yang, Applied Economic Perspectives and Policy **43**, 341 (2021)
[3] E. Nartey, F.K. Aboagye-Otchere, S.N.Y. Simpson, Management Research Review **45**, 398 (2022)
[4] V.A. Thomas, B. Mahanty, Journal of Industrial and Production Engineering **37**, 56 (2020)
[5] W. Duan, H. Ma, D. Xu, *Analysis of the impact of COVID-19 on the coupling of the material flow and capital flow in a closed-loop supply chain.* (2021), Vol. 16
[6] D. Ivanov, Transportation Research Part E: Logistics and Transportation Review **136**, 101922 (2020)
[7] T.J. Richards, B. Rickard, Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie **68**, 189 (2020)
[8] D. Wu, C. Wu, Agriculture **12**, 793 (2022)
[9] P. Chowdhury, S.K. Paul, S. Kaisar, M.A. Moktadir, Transportation Research Part E: Logistics and Transportation Review **148**, 102271 (2021)
[10] B. Yan, X.h. Wu, B. Ye, Y.w. Zhang, Industrial Management & Data Systems (2017)
[11] D. WOODRUFF, *Population biology of infectious-diseases-anderson, rm, may, rm* (1983)
[12] J.D. Sterman, Management science **35**, 321 (1989)
[13] J. Swanson, Journal of the Operational Research Society **53**, 472 (2002)
[14] S. He, Y. Peng, K. Sun, Nonlinear dynamics **101**, 1667 (2020)
[15] D. Ivanov, The International Journal of Logistics Management **33**, 1196 (2022)