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A CLOSED-LOOP SUPPLY CHAIN SUPERNETWORK BASED ON DISRUPTION RISKS IN DYNAMIC ENVIRONMENT

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Abstract. *First of all, this paper develops a 5-tiered closed-loop supply chain network including raw material suppliers, manufacturers, retailers, demand markets and recovery centers by using probability of risk occurrence and risk loss function to express the characteristics of risk management in supply chain network. Then the decision-makers seek profit maximum and satisfaction maximum as their optimization objectives by using the theory of variational inequality. Specifically, a simple cyclic function is used to describe the demand market's seasonal demand. Finally, the model is verified reasonably by numerical example.*
Keywords: Disruption risks, Dynamic environment, Closed-loop supply chain, Supernetwork, Variational inequalities, Projected dynamical system

1. **Introduction.** With the development of economic globalization and the increasing of environmental damage and natural disasters, the disruption risk has become the most important risk. Such risks in supply chain will lead to a variety of problems.

As the impact of the outsourcing practices, the procurement process is becoming even more exposed to risk and disruption [1,2]. Yue and Zhang [3] discussed the risks and impairments caused by them in shipbuilding supply chain. Xanthopoulos et al. [4] studied the disruption problem in supply channel and emphasized the importance of multi-sourcing supply. Sardar and Lee [5] suggests an approach to quantify the border crossing complexity and its impact on supply chain disruption risk in the global outsourcing environment. Xu et al. [6] integrate a defender-attacker game with supply chain risk management, and study the defender's optimal preparation strategy. Feng et al. [7] developed a supply chain supernetwork model with 4-tiered including suppliers, manufacturers, retailers and consumers at demand market, in which the demand for product is seasonal, and the sensitivity of demand to price is another key factor which effects consumers' demand. Moreover, the manufacturers invest the reverse distribution channel for incenting consumers to return more used products.

In this paper, a 5-tiered closed-loop supply chain based on the probability of risk occurrence is developed and described. The demand markets' demand is seasonal, so we use a simple cosine functional form D_k to describe the demand. Specially, the probability of risk occurrence and risk loss function are used to express the characteristics of risk management in supply chain network. Compared with the work of Feng et al. [7], we add the recovery centers to the decision-makers and the probability of risk occurrence and risk loss function to the close-loop supply chain.

The rest of this paper is organized as follows. In Section 2, we analyze and optimize behaviors of decision-makers in the model. In Section 3, we give a numerical example to validate the model. Finally, the paper is concluded in Section 4.

2. **Objectives of the Closed-Loop Supply Chain Network Members.** For simplification, we assume that there are S raw material suppliers, I manufacturers, J retailers, K demand markets, and O recovery centers. All associated symbols and their implications in our paper are given as follows:

Let $f_s(Q^1, t)$ denote the procurement cost of raw material supplier s at time t depending on the vector of the raw material volume $Q^1 = (q_{si})_{\substack{s=1,\dots,S \\ i=1,\dots,I}}$. $q_{si}(t)$ denotes the amount of product transacted from raw material supplier s to manufacturer i at time t; $\rho_{1s}^f(t)$ is the price charged for product by raw material supplier s to manufacturer i at time t. Let $C_{1si}(q_{si}, t)$ denote the unit of transaction cost paid by supplier s.

Hence, the optimality conditions for all suppliers can be described simultaneously using the following evolutionary variational inequality [5-7] with vector field $K_1 = \left\{Q^{1*} \in L^2\left([0,T], R_+^{SI}\right) \middle| q_{si}(t) \geq 0 \ a.e. \ in[0,T], \forall s, i\right\}$

$$\int_0^T \left\{ \left(\frac{\partial f_s(Q^1, t)}{\partial q_{si}^f(t)} + \frac{\partial C_{1si}\left(q_{si}^f, t\right)}{\partial q_{si}^f(t)} - \rho_{1s}^{f*}(t) \right) \times \left(q_{si}(t) - q_{si}^*(t)\right) \right\} dt \geq 0 \tag{1}$$

Let r_{ij} denote the risk loss function and ε denote the probability of risk occurrence. Denote the desirability of retailer j transacting with manufacturer i by $b_{1ij}(h_{ij}, t)$ and the optimality conditions for all manufacturers following with weight value α_i. Let $f_i^r(Q^1, t)$ present the procurement cost from raw materials with recovery rate β_r at time t and $f_i^u(Q^5, t)$ present the procurement cost from reusable materials with recovery rate β_u at time t $\left(Q^5(t) = (q_{io}^b(t))_{\substack{i=1,\dots,I \\ o=1,\dots,O}} \right)$. $\rho_{2i}^f(t)$ denotes the price charged for product by manufacturer i to retailer j at time t. $q_{ij}(t)$ denotes the amount of product transacted from manufacturer i to retailer j at time t $\left(Q^2(t) = (q_{ij}(t))_{\substack{i=1,\dots,I \\ j=1,\dots,J}} \right)$. $q_{io}^b(t)$ denotes the amount of product transacted from recovery center o to manufacturer i at time t. $\rho_{4o}^b(t)$ denotes the price charged for product by recovery center o to manufacturer i at time t and $C_{2si}(q_{si}, t)$ denotes the unit of transaction cost charged for product by manufacturer i to raw material supplier s at time t. Let $C_{1io}\left(q_{io}^b, t\right)$ denote the unit of transaction cost charged for product by manufacturer i to recovery center o at time t and $C_{1ij}(q_{ij}, h_{ij}, t)$ denote the unit of transaction cost charged for product by manufacturer i to retailer j at time t. Finally, the economical costs paid by manufacturer i to retailer j are expressed as $v_{1ij}(h_{ij}, t)$ depending on the degree of relationship h_{ij}.

Hence, the optimality conditions for all manufacturers can be described simultaneously using the following evolutionary variational inequality [5-7] with vector field $K_2 = \left\{ (Q^{1*}, Q^{2*}, Q^{5*}, \lambda_1^*) \in L^2\left([0,T], R_+^{SI+IJ+IO+I}\right) \middle| q_{si}(t) \geq 0, \ q_{ij}(t) \geq 0, \ q_{io}^b(t) \geq 0 \ a.e. \ in[0,T], \ \forall s, i, j, k, o \right\}$ with the LaGrange multiplier $\lambda_1(t) = (\lambda_{1i}(t))_{i=1,\dots,I}$,

$$\int_0^T \left\{ \sum_{s=1}^S \sum_{i=1}^l \left(\frac{\partial f_i^r(Q^1, t)}{\partial q_{si}^f(t)} + \frac{\partial C_{2si}(q_{si}^t, t)}{\partial q_{si}^f(t)} + \rho_{1s}^f(t) - \beta_r \lambda_{1i}(t) \right) \times \left(q_{si}^f(t) - q_{si}^{f*}(t) \right) \right.$$

$$+ \sum_{i=1}^I \sum_{j=1}^J \left(\frac{\partial C_{1ij}(q_{ij}, h_{ij}, t)}{\partial q_{ij}(t)} - \rho_{2i}^f + \frac{\partial r_{ij}(q_{ij}, t)}{\partial q_{ij}(t)} \times \varepsilon + \lambda_{1i}(t) \right) \times \left(q_{ij}(t) - q_{ij}^*(t) \right)$$

$$+ \sum_{i=1}^I \sum_{o=1}^O \left(\frac{\partial f_i^u(Q^5, t)}{\partial q_{io}(t)} + \frac{\partial C_{1io}(q_{io}, t)}{\partial q_{io}(t)} + \rho_{4o}^b(t) - \beta_u \lambda_{1i}(t) \right) \times (q_{io}(t) - q_{io}^*(t))$$

$$+\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\frac{\partial v_{1ij}(h_{ij},t)}{\partial h_{ij}(t)}+\frac{\partial C_{1ij}(q_{ij},h_{ij},t)}{\partial h_{ij}(t)}-\alpha_i\frac{\partial b_{1ij}(h_{ij},t)}{\partial h_{ij}(t)}\right)\times\left(h_{ij}(t)-h_{ij}^*(t)\right)$$

$$+\sum_{i=1}^{I}\left(\beta_r\sum_{s=1}^{S}q_{si}^f(t)+\beta_u\sum_{o=1}^{O}q_{io}(t)-\sum_{j=1}^{J}q_{ij}(t)\right)\times\left(\lambda_{1i}(t)-\lambda_{1i}^*(t)\right)\Bigg\}dt\geq 0 \quad (2)$$

Let $C_j(Q^2,t)$ denote the handling cost. The economical costs paid by retailer j to manufacturer i are expressed as $v_{2ij}(h_{ij},t)$ depending on the degree of relationship h_{ij}. Also let $v_{2jk}(h_{jk},t)$ denote the economical costs between retailer j and manufacturer i. Denote the desirability of retailer j transacting with manufacturer i by $b_{2ij}(h_{ij},t)$. $b_{2jk}(h_{jk},t)$ represent the desirability of retailer j transacting with demand market k, the optimality conditions for all retailers following with weight value α_i. $C_{2ij}(q_{ij},h_{ij},t)$: the unit of transaction cost charged for product by retailer j to manufacturer i at time t; $C_{2jk}(q_{jk},h_{jk},t)$: the unit of transaction cost charged for product by retailer j to manufacturer i at time t; $\rho_{3j}^f(t)$: price charged for product by retailer j to demand market k at time t; $q_{jk}(t)$: amount of product transacted from retailer j to demand market k at time $t\left(Q^3(t)=(q_{jk})_{\substack{j=1,2,\ldots,J\\k=1,2,\ldots,K}}\right)$.

Hence, the optimality conditions for all retailers can be described simultaneously using the following evolutionary variational inequality [5-7] with vector field $K_3=\left\{\left(Q^{2*},Q^{3*},\lambda_2^*\right)\in L^2\left([0,T],R_+^{IJ+Jk+J}\right)\middle|q_{ij}(t)\geq 0,\ q_{jk}(t)\geq 0\ a.e.\ in[0,T],\ \forall i,j,k\right\}$ with the LaGrange multiplier $\lambda_2(t)=(\lambda_{2j}(t))_{j=1,\ldots,J}$,

$$\int_0^T\Bigg\{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\frac{\partial C_{2ij}(q_{ij},h_{ij},t)}{\partial q_{jk}(t)}-\rho_{3j}^f(t)+\lambda_{2j}(t)\right)\times\left(q_{jk}(t)-q_{jk}^*(t)\right)$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\left(\frac{\partial C_{2jk}(q_{jk},h_{jk},t)}{\partial q_{jk}(t)}-\rho_{3j}^f(t)+\lambda_{2j}(t)\right)\times\left(q_{jk}(t)-q_{jk}^*(t)\right)$$

$$+\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\frac{\partial v_{2ij}(h_{ij},t)}{\partial h_{ij}(t)}-\alpha_j\frac{\partial b_{2ij}(h_{ij},t)}{\partial h_{ij}(t)}+\frac{\partial C_{2ij}(q_{ij},h_{ij},t)}{\partial h_{ij}(t)}\right)\times\left(h_{ij}(t)-h_{ij}^*(t)\right)$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\left(\frac{\partial C_{2jk}(q_{jk},h_{jk},t)}{\partial h_{jk}(t)}+\frac{\partial v_{2jk}(h_{jk},t)}{\partial h_{jk}(t)}-\alpha_j\frac{\partial b_{2jk}(h_{jk},t)}{\partial h_{jk}(t)}\right)\times\left(h_{jk}(t)-h_{jk}^*(t)\right)$$

$$+\sum_{j=1}^{J}\left(\sum_{i=1}^{I}q_{ij}(t)-\sum_{k=1}^{K}q_{jk}(t)\right)\times\left(\lambda_{2j}(t)-\lambda_{2j}^*(t)\right)\Bigg\}dt\geq 0 \quad (3)$$

Our focus is on exploring the effect of seasonality in demand, and we consider a simple functional form D_k to describe the demand, in which the cycle length is set to be a year.

$$D_k(\rho_k,w,t)=\left(\tilde{D}-w\rho_k(t)\right)\cdot\left(1-RA_d\cdot\cos(2\pi(t+\phi_d))\right)$$

$$\rho_{3j}^f+\frac{\partial C_{3jk}(q_{jk},h_{jk},t)}{\partial q_{jk}(t)}\begin{cases}=\rho_k(t),\ q_{jk}(t)>0\\ \geq\rho_k(t),\ q_{jk}(t)=0\end{cases}$$

$$a_k(Q^4,t)\begin{cases}=\rho_{ko}(t),\ q_{ko}^b(t)>0\\ \geq\rho_{ko}(t),\ q_{ko}^b(t)=0\end{cases}$$

$$D_k(\rho_k(t)) \begin{cases} \le q_{jk}(t), \ \rho_k = 0 \\ = q_{jk}(t), \ \rho_k > 0 \end{cases}$$

The equilibrium conditions of the demand market can be formulated simultaneously using the following evolutionary variational inequality [5-7] with vector field $K_4 = \Big\{ (Q^{3*}, Q^{4*}, \lambda_3^*) \in L^2\left([0,T], R_+^{JK+KO+K}\right) \big| q_{jk}(t) \ge 0, \ \sum_{o=1}^{p} q_{ko}^b(t) \le r_k \sum_{j=1}^{k} q_{jk}(t) \ a.e. \ in[0,T], \ \forall j,k,o \Big\}$ with the LaGrange multiplier $\lambda_{3k}(t)$ $(\lambda_3(t) = (\lambda_{3k}(t))_{k=1,\dots,K})$

$$\begin{aligned} &\int_0^T \Bigg\{ \sum_{j=1}^{J}\sum_{k=1}^{K} \left(\rho_{3j}^f(t) + \frac{\partial C_{3jk}(q_{jk}, h_{jk}, t)}{\partial q_{jk}(t)} - \rho_k(t) - r_k\lambda_{3k}(t) \right) \times (q_{jk}(t) - q_{jk}^*(t)) \\ &+ \sum_{k=1}^{K}\sum_{o=1}^{O} \left(a_k(Q^4,t) - \rho_{ko}(t) + \lambda_{3k}(t) \right) \times \left(q_{ko}^b(t) - q_{ko}^{b*}(t) \right) \\ &+ \sum_{k=1}^{K}\sum_{o=1}^{O} \left(a_k(Q^4,t) - \rho_{ko}(t) + \lambda_{3k}(t) \right) \times (\rho_k(t) - \rho_k^*(t)) \\ &+ \sum_{k=1}^{K} \left(r_k \sum_{j=1}^{J} q_{jk}(t) - \sum_{o=1}^{O} q_{ko}^b(t) \right) \times (\lambda_{3k}(t) - \lambda_{3k}^*(t)) \Bigg\} dt \ge 0 \end{aligned} \tag{4}$$

Denote the recycling cost by $C_o(Q^4, t)$ for recovery center o. The unusable materials must be sent to the landfill, and the disposal cost is described as $\rho\bar{\chi}_o \sum_{n=1}^{N} q_{ko}^b$, where χ_o is the transformation rate. $C_{4io}(Q_5, t)$: the unit of transaction cost charged for product by recovery center o to manufacturer i at time t; $q_{ko}^b(t)$: amount of product transacted from recovery center o to demand market k at time t $\left(Q^4(t) = (q_{ko})_{\substack{k=1,2,\dots,K \\ o=1,2,\dots,O}} \right)$; $\rho_{ko}(t)$: price charged for product by recovery center o to demand market k at time t; $\rho_k(t)$: market price of product at demand market k at time t; w: the sensitivity of demand to price which implies the degree of relying on price advantage for retailers.

Hence, the optimality conditions for all recovery centers can be described simultaneously using the following evolutionary variational inequality [5-7] with vector field $K_5 = \Big\{ (Q^{4*}, Q^{5*}, \lambda_4^*) \in L^2\left([0,T], R_+^{IO+KO+O}\right) \big| q_{io}^b(t) \ge 0, \ \sum_{i=1}^{m} q_{io}^b(t) \le \chi_o \sum_{k=1}^{o} q_{ko}(t) \ a.e. \ in[0,T], \ \forall i,k,o \Big\}$ with the LaGrange multiplier $\lambda_4(t) = (\lambda_{4o}(t))_{o=1,\dots,O}$.

$$\begin{aligned} &\int_0^T \Bigg\{ \sum_{k=1}^{K}\sum_{o=1}^{O} \left(\frac{\partial C_o(Q^4,t)}{\partial q_{ko}^b(t)} + \rho_{ko}(t) + \rho\bar{\chi} - \chi_o \cdot \lambda_{4o}(t) \right) \times (q_{ko}(t) - q_{ko}^*(t)) \\ &+ \sum_{i=1}^{I}\sum_{o=1}^{O} \left(-\rho_{4o}^b(t) + \frac{\partial C_{4io}(q_{io}^b, t)}{\partial q_{io}^b(t)} + \lambda_{4o}(t) \right) \times \left(q_{io}^b(t) - q_{io}^{b*}(t) \right) \\ &+ \sum_{o=1}^{O} \left(\chi_o \sum_{k=1}^{K} q_{ko}^b(t) - \sum_{i=1}^{I} q_{io}^b(t) \right) \times (\lambda_{4o}(t) - \lambda_{4o}^*(t)) \Bigg\} dt \ge 0 \end{aligned} \tag{5}$$

In equilibrium, the equilibrium material flows and price patterns must satisfy the sum of the optimality conditions (1), (2), (3), (4) and the equilibrium condition (5).

3. **Numerical Example.** Here we provide numerical examples to illustrate the effects of parameters on the equilibrium solutions. These examples have been constructed using two raw material suppliers, two manufacturers, three retailers, two demand markets and two recovery centers. And functions are constructed as follows:

$$f_s(Q^1,t) = 3\left(\sum_{i=1}^{2} q_{si}(t)\right)^2 + \left(\sum_{i=1}^{2} q_{1i}(t)\right)\left(\sum_{i=1}^{2} q_{2i}(t)\right) + 2\left(\sum_{i=1}^{2} q_{si}(t)\right),\ s=1,2;$$

$$f_1^r(Q^1,t) = \left(\beta_r\sum_{s=1}^{2} q_{s1}\right)^2 + \left(\beta_r\sum_{s=1}^{2} q_{s1}\right)\left(\beta_r\sum_{s=1}^{2} q_{s2}\right) + 4;\ C_{1io}(Q^5,t) = 2q_{io}^2(t);$$

$$f_2^r(Q^1,t) = 2\left(\beta_r\sum_{s=1}^{2} q_{s2}\right)^2 + \left(\beta_r\sum_{s=1}^{2} q_{s1}\right)\left(\beta_r\sum_{s=1}^{2} q_{s2}\right) + 1;\ C_{4io}(Q^5,t) = q_{io}^2(t) + 3;$$

$$C_{1si}(Q^1,t) = (q_{si}(t))^2 + 2q_{si}(t);\ C_{2si}(q_{si},t) = 2.5q_{si}^2(t) + 1;\ b_{1ij}(h_{ij},t) = h_{ij}^w(t);$$

$$C_{1ij}(Q^2,h_{ij},t) = 2q_{ij}^2(t) - 1.5h_{ij}(t) + 4;\ C_{2ij}(q_{ij},h_{ij},t) = 0.5q_{ij}^2(t) - h_{ij}(t) + 1;$$

$$C_{2jk}(Q^3,h_{jk},t) = q_{jk}^2(t) - h_{jk}(t) + 2;\ C_{3jk}(q_{jk},h_{jk},t) = 0;\ b_{2ij}(h_{ij},t) = h_{ij}^w(t);$$

$$a_1(Q^4,t) = 0.5\sum_{o=1}^{2}\sum_{k=1}^{2} q_{ko}(t) + 4;\ a_2(Q^4,t) = 0.4\sum_{o=1}^{2}\sum_{k=1}^{2} q_{ko}(t) + 8;$$

$$C_1(Q^4,t) = \left(\sum_{k=1}^{2} q_{k1}(t)\right)^2 + 2\sum_{k=1}^{2} q_{k1}(t)\sum_{k=1}^{2} q_{k2}(t) + 3;\ v_{1ij}(h_{ij},t) = h_{ij}(t) + 2;$$

$$C_2(Q^4,t) = 2\left(\sum_{k=1}^{2} q_{k2}(t)\right)^2 + \sum_{k=1}^{2} q_{k1}(t)\sum_{k=1}^{2} q_{k2}(t) + 1;\ v_{2ij}(h_{ij},t) = h_{ij}(t) + 2;$$

$$C_j(Q^2,t) = \left(\sum_{i=1}^{2}\sum_{j=1}^{3} q_{ij}(t)\right)^2;\ f_i^u(Q^5,t) = \left(\beta_u\sum_{o=1}^{2} q_{2o}(t)\right)^2 + 2\beta_u\sum_{o=1}^{2} q_{2o}(t);$$

$$r_{ij}(Q^2,t) = 6q_{ij}^2(t) + 13q_{ij}(t);\ b_{2jk}(h_{jk},t) = h_{jk}^w(t);\ v_{2jk}(h_{jk},t) = h_{jk}(t) + 1;$$

$$f_i^u(Q^5,t) = \left(\beta_u\sum_{o=1}^{2} q_{1o}(t)\right)^2 + \beta_u\sum_{o=1}^{2} q_{1o}(t) + 3$$

Table 1 shows the changes of shipments transacted between manufacturer 1/manufacturer 2 and retailers 1, 2, 3. The proportion of shipment transacted between manufacturer 1/manufacturer 2 and retailer 1 is the biggest. We can see that, the shipments transacted between manufacturer 1/manufacturer 2 and retailer 1 reduce with the increasing of the probability of risk occurrence. On the opposite side, the bigger the probability of risk occurrence is, the larger the shipments transacted between manufacturer 1/manufacturer 2 and retailers 2, 3 are. That is because the transaction costs between manufacturer 1/manufacturer 2 and retailer 1 are lower and the shipment is bigger. In a word, the bigger the shipment is, the larger the loss caused by the probability of risk occurrence is.

We can easily see from Figure 1, when the price sensitivity w is equal to 1.5, the total amounts of shipments vary over time t. The figure is in line with the trend of sine curve with the minimum value when $t = 0$ or $t = 1$, and with the maximum value when $t = 0.5$. It clearly conforms to the actual situation. And from Figure 1, we can also find that the shipment from manufacturers Q^2 is greater than the total volume of raw material Q^1. It is because that the recovery centers recycle products which will be reused by the manufacturers.

TABLE 1. The shipment and proportion between manufacturer and retailer varying with the probability of risk occurrence

	Manufacturer 1							
Retailer	$\varepsilon = 0.1$	$\varepsilon = 0.15$	$\varepsilon = 0.2$	$\varepsilon = 0.25$	$\varepsilon = 0.3$	$\varepsilon = 0.35$	$\varepsilon = 0.4$	$\varepsilon = 0.45$
1	600	600	599	597	595	593	590	597
%	48.27	48.08	47.88	47.61	47.33	47.06	46.71	46.44
2	389	390	391	392	393	395	397	398
%	31.24	31.25	31.255	31.26	31.265	31.43	31.49	31.57
3	254	258	261	265	269	272	276	279
%	20.43	20.67	20.86	21.13	21.40	21.59	21.85	22.07
	Manufacturer 2							
Retailer	$\varepsilon = 0.1$	$\varepsilon = 0.15$	$\varepsilon = 0.2$	$\varepsilon = 0.25$	$\varepsilon = 0.3$	$\varepsilon = 0.35$	$\varepsilon = 0.4$	$\varepsilon = 0.45$
1	1149	1121	1097	1075	1055	1036	1020	1005
%	56.55	55.28	54.22	53.21	52.33	51.52	50.82	50.12
2	546	558	567	576	583	589	594	599
%	26.87	27.51	28.03	28.51	28.92	29.29	29.60	29.88
3	337	349	359	369	378	386	393	401
%	16.58	17.21	17.75	18.27	18.75	19.19	19.58	20

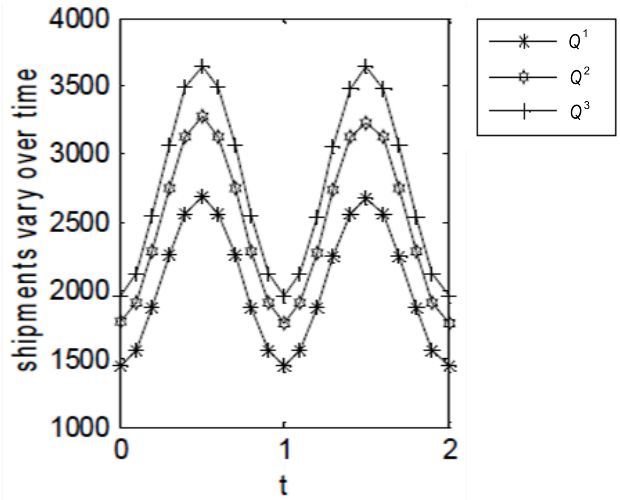

FIGURE 1. The shipment varying over time

4. **Conclusions.** In this paper, we present a 5-tiered closed-loop supply chain supernetwork based on disruption risks, in which the demand markets' demand is seasonal. In order to describe the seasonal demand, we use a simple cyclic function. In a word, the research on supply chain supernetwork equilibrium based on disruption risks helps the firms optimize their risk management, and reduce risk loss. The bigger the shipment is, the larger the loss caused by the probability of risk occurrence is. We should pay more attention to this supply chain risk. We also easily find that the demand of the products is seasonal. In other words, the demand is bigger in the middle of a year. For further research, the model should be used to the service supply chain network for more details.

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