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Research on Coping Strategies of Supply Disruption under Stochastic Demand

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ABSTRACT. *Supply disruptions often appear in supply chain. Using appropriate coping strategies can help firms to compensate the economic losses effectively. In this paper, we construct a supply chain consisting of single supplier and single retailer. By introducing interruption time, we study the coping strategies of retailer after supply disruption under stochastic demand, including taking no countermeasures, assisting supplier in productivity recovery by cost-sharing of productivity recovery and purchasing products to the spot market. Through numerical analysis, we analyze the impact of the interruption time on the retailer's purchase quantity and compare the profit changes of all parties in the supply chain under different strategies, which provides guidance for the enterprises in the supply chain to deal with the supply disruption effectively.*

KEYWORDS: *stochastic demand, supply disruption, assistance, spot market, penalty*

1. Introduction

In recent years, various natural disasters, fires, machine failures, political factors and other emergencies often cause enterprises to fail to operate or even close down. The downstream enterprises in the supply chain often suffer huge losses from supply disruptions caused by emergencies in the upstream. For example, in 2018, due to ZTE violated American regulations, American government prohibited national companies from providing any chips, software and technology to ZTE for seven years, resulting in losses amounting to ¥7.26 billion. According to the American Production and Inventory Control Society (APICS) industry report, 66% of managers believe that supply disruption is the most important risk in the supply chain. In order to reduce the negative impact of supply disruptions on downstream companies and supply chain performance, managers must take effective measures to manage supply disruptions scientifically and effectively.

At present, the research on supply disruption mainly includes multi-suppliers procurement (e.g., He et al. 2019, Kumar et al. 2018), inventory management (e.g., Schmitt and Snyder 2012, Jakšič and Fransoo 2015) before the disruption to reduce the risk of supply disruption, financial assistance between supply chain enterprises

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

(e.g., Babich 2010, Wadecki et al. 2010, Zhou and Hou 2017) before the disruption to improve production reliability, and the purchase of back-up supplier (e.g., Chen and Yang 2014, Zhou et al. 2017) after the disruption to reduce the losses caused by supply disruptions. The above research focused on improving production reliability and reducing the risk of disruption, and did not consider the issue of productivity recovery after supply disruption. The assistance to upstream production companies for productivity recovery is a hot topic of current research. The assistance includes price incentives, cost-sharing of productivity recovery, and so on. There are scholars who have studied the assistance of price incentives. Hu et al. (2013) considered how the buyer could use the price incentive to motivate the supplier's investment in production recovery when incentives happen before or after the disruption. Some scholars have also studied sharing the cost of productivity recovery to assist upstream producers in productivity recovery. Li et al. (2016) compared the manufacturer, in a better financial situation, uses ex-ante penalty decision and ex-post cost-sharing to compel the supplier to recover its production capability as much as possible. In addition, the urgent purchase of products to the spot market is also one of the effective measures to deal with the supply disruptions. Li et al. (2010) considered that retailers can order products to the spot market to meet demand after the supply disruption. Yao et al. (2016) constructed a model using the spot market to cope with supply disruption under supply chains competition, and analyzed the impact of disruption parameters to the competitive supply chains and its members under supply disruption.

The existing literatures have separately studied the assistance help upstream production enterprises carry out productivity recovery and purchasing products to the spot market to reduce the risk of supply disruption. However, there are few considerations on how the proportion of cost-sharing of productivity recovery and the purchase price of the spot market affect the profit of the supply chain, and there is no deep analysis of the impact of the interruption time on the productivity recovery. Based on the randomness of the interruption occurrence, the paper constructs a supply chain consisting of single supplier and single retailer. By introducing interruption time, the paper studies the coping strategies of retailer after supply disruption under stochastic demand, including taking no countermeasures, assisting supplier in productivity recovery by cost-sharing of productivity recovery and purchasing products to the spot market. Through numerical analysis, the paper analyzes the impact of the interruption time on the retailer's purchase quantity and compares the profit changes of all parties in the supply chain under different strategies, which provides guidance for the enterprises in the supply chain to deal with the supply disruption effectively.

2. The model

In this paper, we consider a two-stage supply chain consisting of single supplier and single retailer. Before the beginning of sales cycle, the retailer signs a contract to specify the order quantity, contract period and other information with the supplier through investigating market demand. Supplier may encounter unexpected events at

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

any time in the production cycle. After the occurrence of unexpected events, the productivity of supplier suddenly becomes zero. In the face of this supply disruption, the retailer can adopt the following three strategies to deal with the problem: (1) taking no countermeasures; (2) assisting supplier in productivity recovery by cost-sharing of productivity recovery; (3) purchasing products to the spot market. We assume if the retailer does not promise to provide cost-sharing of productivity recovery after the disruption, the supplier will not take measures to recovery productivity. Purchasing products to the spot market will face the risk that the purchase price is higher than the contract purchase price of the original supplier. The overall operation process of the supply chain is shown in Figure 1. We list the notation in Table 1.

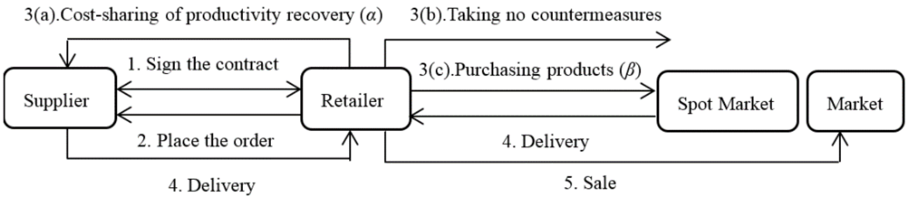


Figure. 1 Supply chain flow diagram of the operation.

Table 1 Summary of key notations.

X:	demand
$F(x)/f(x)$:	distribution/ density function of demand X
μ:	the mean of demand X, $u = \int_0^\infty xf(x)dx$
w:	wholesale price the supplier sets in the contract signed before the disruption
v:	unit salvage value of the surplus stock
p:	unit market price, $p > w > v$
q:	purchase quantity of the retailer after disruption
q_0:	order quantity of the retailer in the contract signed before the disruption
T_0:	contract period
T:	interruption time, $0 \le T \le T_0$, $T \in N$
e:	unit non-delivery penalty by the supplier
C_s:	unit production cost in the case of no disruption
C_e:	unit production cost in the case of disruption, $c_e > c_s$
g_r:	unit non-delivery loss by the retailer
α:	the sharing rate of productivity recovery cost given by the retailer, $0 \le \alpha \le 1$
β:	the coefficient of the wholesale price from the spot market, $\beta > 1$

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

3. The baseline case without disruption

We first study the benchmark case without disruption. The retailer's expected sale, $S(q)$, is thus given by

$$S(q) = \min\{q, X\} = \int_0^q xf(x)dx + \int_q^\infty qf(x)dx = q - \int_0^q F(x)dx$$

Let $I(q)$ be the expected left over inventory, so $I(q) = \int_0^q (q-x)f(x)dx = q - S(q)$.

Let $L(q)$ be the expected shortage, so $L(q) = \int_q^\infty (x-q)f(x)dx = \mu - S(q)$.

When there is no supply disruption, the expected profit function of the retailer is expressed as

$$\begin{aligned}\Pi_r(q) &= pS(q) + vI(q) - g_r L(q) - wq \\ &= q(p + g_r - w) - (p - v + g_r)\int_0^q F(x)dx - g_r\mu \end{aligned} \tag{1}$$

By taking the derivative of equation (1) with respect to *q*, we can get

$$q_0 = F^{-1}\left(\frac{p + g_r - w}{p - v + g_r}\right) \tag{2}$$

4. The strategies for coping with supply disruptions

4.1 Taking no countermeasures

Before the supply disruption, we assume the supplier produces the product at the rate of $h_0 = \frac{q_0}{T_0}$ per time unit in the normal state designated for on-time delivery. When supply disruption happens, the supplier's productivity transfers h_0 into 0 and the supplier can't supply products for the retailer. At this point, according to the contract, the supplier shall pay the retailer the unit non-delivery penalty *e*. If the retailer does not take action after an emergency, the quantity supplied by the supplier within the contract period is $q_{s1} = h_0 T$. The expected profit function of the supplier is expressed as

$$\Pi_{s1} = (w - c_s)h_0 T - (q_0 - h_0 T)e \tag{3}$$

The expected profit function of the retailer is expressed as

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

$$\begin{aligned}\Pi_{r1} &= pS(h_0T)+vI(h_0T)-g_rL(h_0T)-wh_0T+(q_0-h_0T)e \\ &= h_0T(p+g_r-w)-(p-v+g_r)\int_0^{h_0T}F(x)dx-g_r\mu+(q_0-h_0T)e\end{aligned} \quad (4)$$

The expected profit function of the supply chain is expressed as

$$\Pi_1=\Pi_{s1}+\Pi_{r1}=pS(h_0T)+vI(h_0T)-g_rL(h_0T) \quad (5)$$

4.2 Assisting supplier in productivity recovery by cost-sharing of productivity recovery

After the supply disruption, the retailer is committed to helping the supplier recovery production by sharing the productivity recovery costs with α proportion. If the resource input of the supplier to recovery production is more, the productivity will recover faster, and $z = c_e - c_s$ is defined as the level of the supplier's production recovery efforts. Let the productivity in the recovery period be $h = kzt^2$, where k is the productivity recovery coefficient of the supplier. The productivity recovery time T_1 meets $kzT_1^2 = h_0$, so productivity recovery time T_1 becomes $\sqrt{\frac{q_0}{T_0k(c_e-c_s)}}$. It can be divided into productivity recovery within the contract period and productivity non-recovery within the contract period whether the supplier can complete the productivity recovery within the contract period. The specific process is shown in Figure 2(a) and Figure 2(b).

4.2.1 Productivity recovery within the contract period

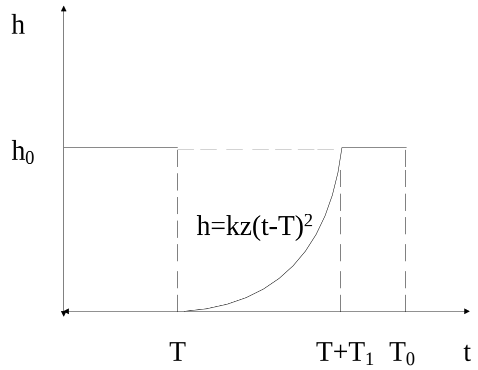


Figure. 2(a) Productivity recovery process.

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

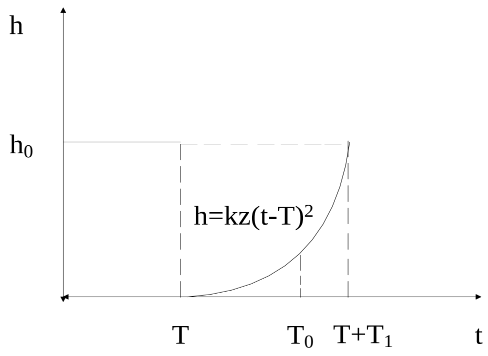


Figure. 2(b) Productivity non-recovery process.

If the supplier can complete the productivity recovery within the contract period, it satisfies $T+T_1 \le T_0$, so interruption time T meets $0 \le T \le T_0 - \sqrt{\dfrac{q_0}{T_0 k(c_e - c_s)}}$. The recovery yield q_1 becomes $\int_{\mathrm{T}}^{\mathrm{T}+T_1} kz(t-\mathrm{T})^2 dt = \frac{1}{3}k(c_e - c_s)T_1^3$. The non-delivery q_2 becomes $h_0T_1 - q_1$. The total capacity q_{sb} becomes $h_0T_0 - q_2$. When the retailer shares the supplier's productivity recovery cost with α proportion, the expected profit function of the supplier is expressed as

$$\Pi_{sb} = wq_{sb} - c_s(q_{sb} - q_1) - (1-\alpha)c_e q_1 - q_2 e \tag{6}$$

The expected profit function of the retailer is expressed as

$$\begin{aligned}\Pi_{rb} &= pS(q_{sb}) + vI(q_{sb}) - g_r L(q_{sb}) - wq_{sb} + eq_2 - \alpha c_e q_1 \\ &= q_{sb}(p + g_r - w) - (p - v + g_r)\int_0^{q_{sb}} F(x)dx - g_r\mu + eq_2 - \alpha c_e q_1\end{aligned} \tag{7}$$

The expected profit function of the supply chain is expressed as

$$\Pi_b = \Pi_{sb} + \Pi_{rb} = pS(q_{sb}) + vI(q_{sb}) - g_r L(q_{sb}) - c_s(q_{sb} - q_1) - c_e q_1 \tag{8}$$

4.2.2 Productivity non-recovery within the contract period

If the supplier can't complete the productivity recovery within the contract period, it satisfies $T+T_1 > T_0$, so interruption time T meets $T_0 - \sqrt{\dfrac{q_0}{T_0 k(c_e - c_s)}} < T \le T_0$.

The recovery yield q_3 becomes $\int_{\mathrm{T}}^{T_0} kz(t\text{-}\mathrm{T})^2 dt = \frac{1}{3}k(c_e - c_s)(T_0 - T)^3$. The non-

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

delivery q_4 becomes $h_0(T_0-T)-q_3$. The total capacity q_{sb1} becomes h_0T+q_3 .When the retailer shares the supplier's productivity recovery cost with α proportion, the expected profit function of the supplier is expressed as

$$\Pi_{sb1}=h_0T(w-c_s)+q_3[w-(1-\alpha)c_e]-q_4e \tag{9}$$

The expected profit function of the retailer is expressed as

$$\begin{aligned}\Pi_{rb1}&=pS(q_{sb1})+vI(q_{sb1})-g_rL(q_{sb1})-wq_{sb1}+eq_4-\alpha c_eq_3\\&=q_{sb1}(p+g_r-w)-(p-v+g_r)\int_0^{q_{sb1}}F(x)dx-g_r\mu+eq_4-\alpha c_eq_3\end{aligned} \tag{10}$$

The expected profit function of the supply chain is expressed as

$$\Pi_{b1}=\Pi_{sb1}+\Pi_{rb1}=pS(q_{sb1})+vI(q_{sb1})-g_rL(q_{sb1})-c_sh_0T-c_eq_3 \tag{11}$$

4.3 Purchasing products to the spot market

In the event of a supply disruption, the retailer has the option to reduce its own losses by purchasing the products q_{sm} to the spot market at βw price. The expected profit function of the retailer is expressed as

$$\begin{aligned}\Pi_{rm}(q_{sm})&=pS(q_{sm}+h_0T)+vI(q_{sm}+h_0T)-g_rL(q_{sm}+h_0T)-wh_0T-\beta wq_{sm}+e(q_0-h_0T)\\&=q_{sm}(p+g_r-\beta w)-(p-v+g_r)\int_0^{q_{sm}+h_0T}F(x)dx+h_0T(p+g_r-w-e)-g_r\mu+eq_0\end{aligned} \tag{12}$$

By taking the derivative of equation (12) with respect to q_{sm}, we can get

$$q_{sm}^*=F^{-1}\left(\frac{p+g_r-\beta w}{p-v+g_r}\right)-h_0T \tag{13}$$

Substituting equation (13) into equation (12), the expected profit function of the retailer is expressed as

$$\begin{aligned}\Pi_{rm}&=F^{-1}\left(\frac{p+g_r-\beta w}{p-v+g_r}\right)(p+g_r-\beta w)+h_0T(\beta w-w-e)\\&\quad-(p-v+g_r)\int_0^{F^{-1}\left(\frac{p+g_r-\beta w}{p-v+g_r}\right)}F(x)dx-g_r\mu+eq_0\end{aligned} \tag{14}$$

The expected profit function of the supplier is expressed as

$$\Pi_{sm}=h_0T(w-c_s)-(q_0-h_0T)e \tag{15}$$

The expected profit function of the supply chain is expressed as

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

$$\Pi_m = \Pi_{sm} + \Pi_{rm} = pS(q^*_{sm} + h_0T) + vI(q^*_{sm} + h_0T) - g_r L(q^*_{sm} + h_0T) - c_s h_0 T - \beta w q^*_{sm} \quad (16)$$

If the retailer chooses to purchase products to the spot market to cope with the supply disruption ($q^*_{sm} > 0$), it meets

$$1 < \beta < \frac{p + g_r - F(h_0T)(p - v + g_r)}{w} \quad (17)$$

Lemma1. q_{s1} increases as T increases; q^*_{sm} decreases as T increases; When productivity completes recovery, q_{sb} remains stable as T increases; When productivity can't complete recovery, q_{sb1} increases as T increases.

Proof $\frac{dq_{s1}}{dT} = h_0 > 0$, $\frac{dq^*_{sm}}{dT} = -h_0 < 0$, $\frac{dq_{sb}}{dT} = 0$, $\frac{dq_{sb1}}{dT} = -k(c_e - c_s)(T_0 - T)^2 + h_0$, and when T meets $T_0 - \sqrt{\frac{q_0}{T_0 k (c_e - c_s)}} < T \le T_0$, $\frac{dq_{sb1}}{dT} > 0$.

5. Numerical simulation

When the upstream supplier of the two-stage supply chain encounters supply disruption, the retailer can take no countermeasures, assist supplier in productivity recovery by cost-sharing of productivity recovery and purchase products to the spot market to deal with the supply disruption. We assume that the market demand that the retailer faces follows a normal distribution with $X \sim N(10000, 500^2)$, and the relevant parameters are shown in Table 2.

Table 2 The value of the relevant parameters.

T_0	p	c_s	c_e	k	w	v	e	g_r	α	β	T
30	100	30	90	0.6	60	40	30	48	[0,1]	(1,2.46]	[0, 30]

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

5.1 The impact of the interruption time on the retailer's purchase quantity

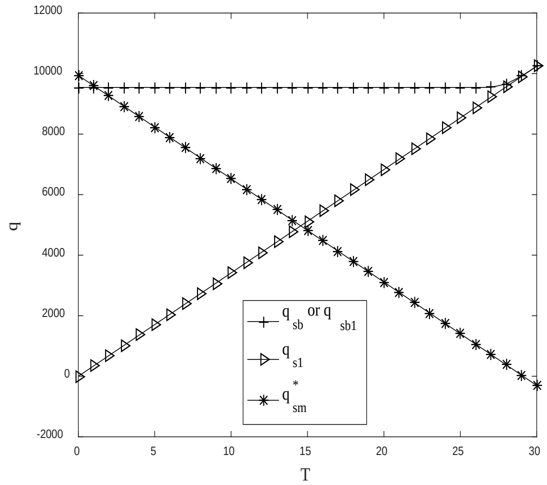


Figure. 3 The impact of the interruption time on the retailer's purchase quantity (β =1.5).

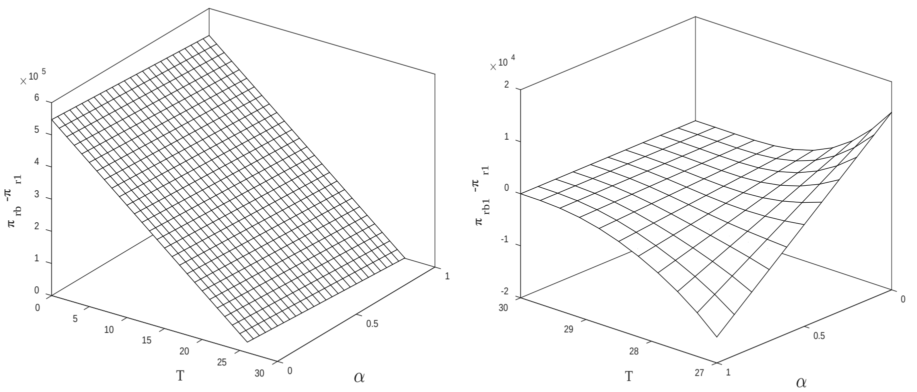
As Fig.3 illustrates, q_{s1} and q_{sm}^{*} are a monotone function of *T*. q_{s1} increases as *T* increases and q_{sm}^{*} decreases as *T* increases. Under the strategy of taking no countermeasures, due to the products supplied by supplier increase as *T* increases, making the retailer's purchase quantity and profit increase. Therefore, the retailers that have single supplier can take preventive measures in advance as much as possible to prevent upstream suppliers from interrupting early and bringing huge losses. Under the strategy of purchasing products to the spot market, with the increase of *T*, products supplied by supplier increase as the original supplier gradually completes production recovery. Therefore, the retailer can appropriately reduce the purchase quantity of products to the spot market with higher purchase price to reduce losses. Under the assistance strategy, when $0 \le T \le T_0 - \sqrt{\dfrac{q_0}{T_0 k(c_e - c_s)}}$ $(0 \le T \le 26)$, the supplier can complete the productivity recovery within the contract period. The total capacity of the supplier during the contract period remains unchanged. When $T_0 - \sqrt{\dfrac{q_0}{T_0 k(c_e - c_s)}} < T \le T_0$ $(27 \le T \le 30)$, the supplier cannot complete the productivity recovery within the contract period. With the increase of *T*, the total trading quantity and profits of retailer and supplier increase, so it is particularly important to take measures to prolong interruption occurrence.

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

5.2 The comparison of profits under three strategies

5.2.1 The comparison of profits under assistance strategy and taking no countermeasures

Fig.4 displays the change of the profit difference between retailers under assistance strategy and taking no countermeasures with T and α. Under the productivity recovery within the contract period, the profit difference between retailers under two strategies remains plus value. Under the productivity non-recovery within the contract period, the profit difference between retailers under two strategies remains plus value when the beginning of interruption occurrence and the lower sharing rate of productivity recovery cost. And the profit difference between retailers under two strategies decreases as α increases. Comparing taking no countermeasures, the profit of retailer under assistance strategy decreases as α increases. For retailer, the profit difference is mostly plus value in the case of T and α change, so the assistance strategy has advantages over taking no countermeasures, but too high sharing rate of productivity recovery cost will hurt the retailer's own profit.

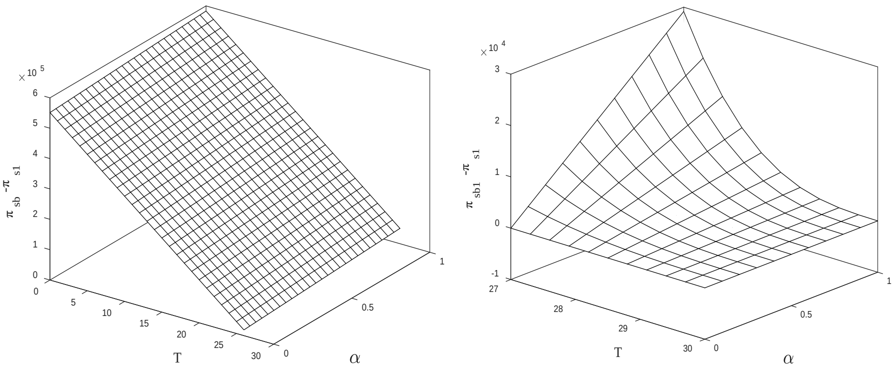


(a) Productivity recovery (b) Productivity non-recovery

Figure. 4 The change of the profit difference between retailers with T and α.

Fig.5 displays the change of the profit difference between suppliers under assistance strategy and taking no countermeasures with T and α. The profit difference between suppliers under two strategies always remains plus value. And the profit difference between suppliers under two strategies increases as α increases. Comparing taking no countermeasures, the profit of retailer under assistance strategy increases as α increases. For supplier, the assistance strategy is more advantageous than taking no countermeasures, and appropriately increasing the sharing rate of productivity recovery cost is conducive to improving the profits of supplier.

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113



(a) Productivity recovery (b) Productivity non-recovery

Figure. 5 The change of the profit difference between suppliers with T and α.

5.2.2 The comparison of profits under purchasing products to the spot market and taking no countermeasures

Fig.6 displays the change of the profit difference between retailers under purchasing products to the spot market and taking no countermeasures with T and β. The profit difference between retailers under two strategies always remains plus value. For retailers, purchasing products to the spot market is more advantageous than taking no countermeasures. Since the suppliers under two strategies do not carry out activities of productivity recovery, the profits of the suppliers under two strategies are the same.

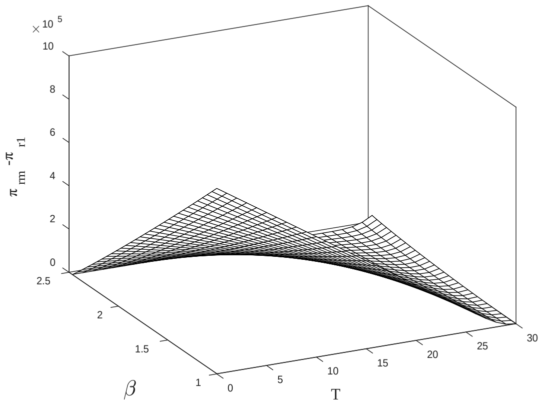


Figure. 6 The change of the profit difference between retailers with T and β.

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

5.2.3 The comparison of profits under purchasing products to the spot market and assistance strategy

Table 3 displays the value of parameter of the comparison of retailer's profits under purchasing products to the spot market and assistance strategy with *T*, α and β. As is shown Table 3, taking *T* as the premise of profit comparison, let the profit of retailer under purchasing products to the spot market with β is greater than the maximum profit of retailer under the assistance strategy with α, so the range of β under purchasing products to the spot market can be calculated. When $1 < \beta \leq 1.48$, the retailer prefers to purchase products to the spot market to deal with the disruption. Due to the same supplier's profits under purchasing products to the spot market and taking no countermeasures, the supplier's profit comparison under purchasing products to the spot market and assistance strategy is consistent with the supplier's profit comparison under taking no countermeasures and assistance strategy. For supplier, the assistance strategy is superior to purchasing products to the spot market.

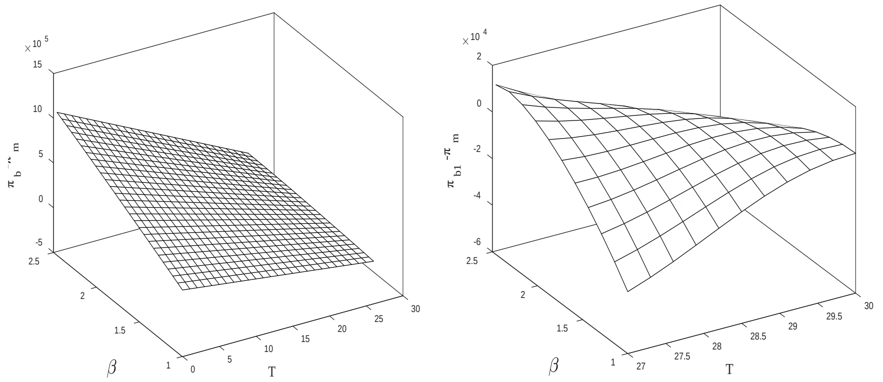
Table 3 The value of parameter under the comparison of retailer's profits.

T	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\leq\beta$	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48
T	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
$\leq\beta$	1.48	1.48	1.48	1.53	1.53	1.53	1.53	1.53	1.53	1.58	1.58	1.63	1.68	2.46	2.46	

5.2.4 The comparison of the profits of supply chain under assistance strategy and purchasing products to the spot market

Fig.7 displays the change of the profit difference between supply chains under assistance strategy and purchasing products to the spot market with T and β. The profit difference between supply chains under two strategies presents plus and minus values. At most times of interruption occurrence and higher purchase prices to spot market, the profit difference between supply chains under two strategies is plus value. For the whole supply chain, the profit difference is mostly plus value in the case of T and β change, so the assistance strategy is superior to purchasing products to the spot market.

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113



(a) Productivity recovery (b) Productivity non-recovery

Figure. 7 The change of the profit difference between supply chains with T and β.

6. Conclusion

The paper considers a two-stage supply chain consisting of single supplier and single retailer and studies the coping strategies of retailer after supply disruption under stochastic demand, including taking no countermeasures, assisting supplier in productivity recovery by cost-sharing of productivity recovery and purchasing products to the spot market. Through numerical analysis, analyzing the impact of the interruption time on the retailer's purchase quantity and comparing the profit changes of all parties in the supply chain under different strategies. Through theoretical analysis and numerical calculation, the following management enlightenment can be obtained. Firstly, the randomness of the interruption occurrence will affect the productivity recovery of the supplier. When T meets $0 \le T \le T_0 - \sqrt{\frac{q_0}{T_0 k(c_e - c_s)}}$, the supplier can complete productivity recovery within the contract period, and the total capacity of the supplier remains unchanged as T increases. When T meets $T_0 - \sqrt{\frac{q_0}{T_0 k(c_e - c_s)}} < T \le T_0$, the supplier can't complete productivity recovery within the contract period, and the total capacity of the supplier increases as T increases. Secondly, for supplier, the assistance strategy is more advantageous in dealing with the supply disruption. Thirdly, for retailer, the lower purchase price to the spot market makes it be willing to purchase products to the spot market to cope with the supply disruption. Fourthly, for the whole supply chain, the assistance strategy is more advantageous to deal with the supply disruption at most times of interruption occurrence and higher purchase prices to spot market. The conclusions of this paper have a good guiding significance for the

ISSN 2616-5902 Vol. 1, Issue 1: 99-112, DOI: 10.25236/AJBM.190113

operation and management of supply chain enterprises suffering from supply disruption.

There are still many ways to deal with the supply disruption, and the combination of multiple strategies can be studied. In addition, the unit non-delivery penalty considered in this paper is an exogenous variable, which can be further introduced into the decision-making problem of the supply chain as a decision variable.

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