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Coordinating the Assembly System Based on Compensation Mechanism Under Supply Disruption

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Abstract: A well-coordinated assembly system plays an important role in an enterprise's strategic management. As the uncertainty of the supply chain is increasing, coordinating the assembly system effectively under supply disruption becomes a critical success factor for a global supply chain system. In this study, we consider an assembly system with two suppliers and one manufacturer and formulate the model of each partner with bonus policy under supply disruption. The optimal decision of each partner is analyzed under decentralized decision. Then we optimize the total cost of assembly system under centralized decision which is regarded as the benchmark. Furthermore, to achieve this benchmark, the compensation mechanism is designed to coordinate the assembly system under supply disruption. At last, the sensitivity is analyzed and the numerical analysis shows that our compensation mechanism is reasonable and effective.

Key words: Assembly system, compensation mechanism, supply disruption, bonus policy

INTRODUCTION

In recent years, the uncertainty of assembly system in upstream supply chain increased significantly due to influence of natural disasters, strikes, terrorist attacks and political instability and other factors. In 2000 Philips Semiconductor Factory's fire lead to Ericsson's supply disruptions of the chip which caused the loss of 1.8 billion Ericsson and 4% of market share loss. In July 2010, Hitachi's unexpected shortage of car engine control part resulted in Nissan's plant shutdown for 3 days in Japan and the production of 1.5 million cars affected. In March 2011, Japan 9 earthquakes in northeast region devastated the area of industrial enterprises. Car production of three major Japanese automakers, Toyota, Honda and Nissan are affected by the disruption of supply chain and some joint ventures in China also had different levels of supply disruptions. These examples illustrate that, as supply chains are extended by outsourcing and stretched by globalization, disruption risks and lack of visibility into a supplier's status can both worsen.

Supply chain risk management has attracted interest from both researchers and practitioners in operations management. Sodhi and Chopra (2004) provided a diverse set of supply disruption examples. Various operational tools that deal with supply disruptions have been studied: multisourcing (Anupindi and Akella, 1993; Tomlin, 2009; Babich *et al*., 2007), alternative supply sources and backup production options (Serel *et al*., 2001; Kouvelis and Milner, 2002; Babich, 2006), flexibility (Van Mieghem, 2003; Tomlin and Wang, 2005) and supplier selection (Deng and Elmaghraby, 2005). For a recent review of supply-risk literature (Tang, 2006).

These and the majority of other papers in the supply-risk literature assume that the occurrence of supply disruptions is known to both the suppliers and the manufacturer. In contrast, we assume that occurrence of supply disruption partially asymmetric between the suppliers and the manufacturer. Tomlin (2009) studied a model where the manufacturer faces two suppliers, one with known and the other with unknown reliability. The manufacturer learns about the latter supplier's reliability through Bayesian updating. In our model, information is also revealed, but through a contract choice rather than through repeated interactions. Gurnani and Shi (2006), a buyer and supplier had differing estimates of the supplier's reliability. Unlike our setting, in assembly system with two suppliers and one manufacturer, the supplier and the manufacturer know the disruption time but the other supplier don't.

In the operations contracting literature, Parlar and Berkin (1991), Moinzadeh and Aggarwal (1997), Ozekici and Parlar (1999). Rosenthal (2008) and other scholars has studied the uncertain delivery time caused by supply disruption. However, the above literatures don't consider how to coordinate the assembly system in case of supply

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disruption. To address these gaps in the current literature, we investigate the interaction between supplier's crashing decision and collaborative policies in case of supply disruption. We address the following questions:

- What are suppliers' optimal decisions for each partner in this assembly system in case of supply disruption?
- What is the best solution under supply disruption for the assembly system?
- How would the manufacturer eliminate the effect of supply disruption, achieve supply coordination and optimize its operational cost?

In answering these questions, we limit our consideration within two-suppliers and one-manufacturer system in case of one supplier's disruption. We construct suppliers' and manufacturer's model that the supplier in supply disruption make the decision of crashing time to optimize its operational cost. Then we set the benchmark that optimal crashing will be derived from aspect of the whole assembly system. In order to achieve the benchmark, we offer the compensation policies and examine how the manufacturer uses this policy to coordinate the suppliers under supply disruption. Finally, numerical and sensitive analysis is provided to illustrate our useful model.

THE MODEL DESCRIPTION

Consider a two-echelon assembly system with two suppliers and single manufacturer, while final product of manufacturer is assembled from the two kind of key components provided by the two suppliers. The initial inventories of suppliers' components are both zero. The agreed delivery time from the components production to the delivery time point, when the manufacturer receives the components, is determined which is called agreed delivery time T_i (i = 1,2). The suppliers' actual delivery time t_i is random because of certain supply emergence, so t_1 and t_2 stand for the actual delivery time.Their probability distributions are respectively f (t_1) and g t_2.

The manufacturer's delivery time from its beginning of production to delivery point of final product is determined which is defined as T_m. The manufacturer's beginning time of its production is the actual delivery time point of two supplier's components. When the manufacturer both receives the matching quantity of component 1 and 2, it begins to assemble. If either delivery of the two suppliers is delayed, the manufacturer's assembly time will be postponed, (Fig. 1).

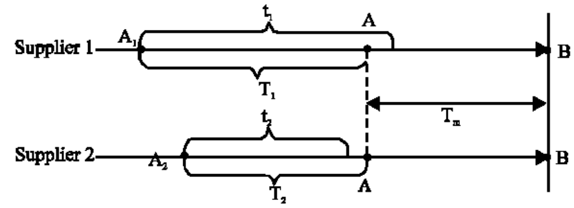

Fig. 1: The related decision variables in suppliers' delivery

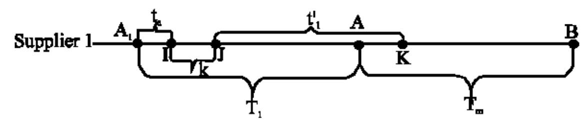

Fig. 2: Disruption of the supplier's production

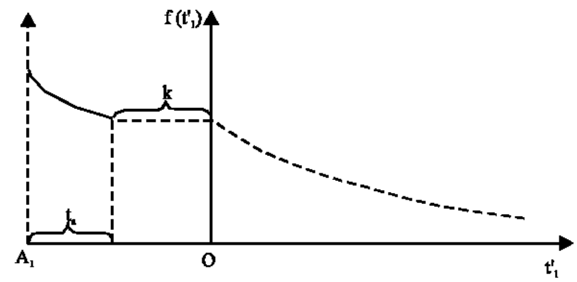

Fig. 3: Distribution of f (t'$_1$)

Under bonus policy, two suppliers have determined their agreed delivery time T_1 and T_2 and started production. But in the production process, a certain supplier (supplier 1 taken as an example in this paper) is disrupted which is lasting for period k (k<T_1) (Fig. 2).

As illustrated in Fig. 2, the interval of point I and J represents the disruption period k of the supplier. The sum of period t_a and t_1 is the normal delivery time t_1 without disruption. Point A_1 stands for the starting time point of the supplier and point A is the delivery time point specified by the manufacturer. The interval of point A_1 and A is T_1 which the agreed delivery time of the supplier.

To compensate for the losses caused by production disruptions, supplier 1 will crash the delivery time. Let crashing cost per unit time is γ.To make the problem meaningful, we assume $\gamma<p_1$ without loss of generality. Before the disruption time point I, supplier 1 has taken production for period t_a and $t_a+k<T_1$ which means that reproduction time point of supplier 1 is ahead of the delivery time point A specified by the manufacturer. Let the actual delivery time of supplier 1 after disruption is t'_1 which obeys the probability distribution of f (t'_1) which is illustrated (Fig. 3).

As shown in Fig. 3, Point A_1 stands for the starting time point of the supplier and after period t_a the supplier

1 is disrupted. The disruption lasts for period k and point o is the reproduction point of supplier 1. We assume that disruption and crashing of supplier 1 will not affect the actual delivery time t_1, then $t'_1+t_a = t_1$ and

$$f(t'_1+t_a)=f(t_1)=\begin{cases}\lambda_1 e^{-\lambda_1(t'_1+t_a)}, & t'_1>0\\ 0, & \text{other}\end{cases}\quad(\lambda_1>0) \tag{1}$$

So the expression $f(t'_1)$ can be rewritten as follows:

$$f(t'_1)=\begin{cases}\lambda_1 e^{-\lambda_1 t'_1}, & t'_1>0\\ 0, & \text{other}\end{cases}\quad(\lambda_1>0) \tag{2}$$

The object is to determine the optimal crashing time of t_c which is best for supplier 1 or the assembly system. The other variables and parameters are as follows:

Decision variables: t_c the crashing time of supplier 1, $t_c>k$
Parameters and variables:

- T_1 the agreed delivery time of supplier 1
- T_2 the agreed delivery time of supplier 2
- t'_1 the actual delivery time of supplier 1 after disruption
- t_2 the actual delivery time of supplier 2
- t_a the production period of supplier 1 before disruption
- p_1 penalty cost per unit time and unit quantity for supplier 1
- p_2 penalty cost per unit time and unit quantity for supplier 2
- p_m penalty cost per unit time and unit quantity for the manufacturer
- h_1 inventory holding cost per unit time and unit quantity for supplier 1
- h_2 inventory holding cost per unit time and unit quantity for supplier 2
- b_1 unit bonus per ahead of unit agreed delivery time for supplier 1
- b_2 unit bonus per ahead of unit agreed delivery time for supplier 2
- k the disruption period of supplier 1
- γ the crashing cost of supplier per unit time
- δ the disruption loss of supplier 1 per unit time
- $f(t'_1)$ probability density function of actual delivery time for supplier 1 under crashing
- $F(t'_1)$ cumulative probability distribution function for supplier 1 under crashing with F (.) continuous, nondecreasing and differentiable.
- $g(t_2)$ probability density function of actual delivery time for supplier 2
- $G(t_2)$ cumulative probability distribution function for supplier 1 with G (.) continuous, nondecreasing and differentiable

OPTIMAL SOLUTION UNDER DECENTRALIZED DECISION WITH BONUS POLICY

We first study the choice of supplier 1 under decentralized decision. The supplier will determine optimal t_c to minimize its total cost. After disruption the delivery time of supplier 1 becomes t'_1 and through the crashing time of t_c the actual delivery time of supplier 1 after disruption becomes t'_1-t_x, then the cost function is:

$$\begin{aligned}TC^d_{s_1}(t_c)=&\,p_1\int_{T_1-k-t_a+t_c}^{\infty} f(t'_1)(t'_1+k+t_a-t_c-T_1)dt'_1\\ &+h_1\int_0^{T_1-k-t_a+t_c} f(t'_1)(T_1-k-t_a-t'_1+t_c)dt'_1\\ &+h_1\int_0^{T_1-k-t_a+t_c}\int_{T_2}^{\infty} f(t'_1)g(t_2)(t_2-T_2)dt'_1dt_2\\ &+h_1\int_{T_1-k-t_a+t_c}^{\infty}\int_{t'_1-t_c-T_1+k+t_a+T_2}^{\infty} f(t'_1)g(t_2)(t_2-T_2+T_1-t'_1+t_c-k-t_a)dt'_1dt_2\\ &-b_1\int_0^{T_1-k-t_a+t_c} f(t'_1)(T_1-k-t_a-t'_1+t_c)dt'_1+\gamma t_c+k\delta\end{aligned} \tag{3}$$

Where, the first term stands for the penalty cost of supplier 1 under crashing condition and the second, third and fourth term represent inventory holding cost of supplier 1 with crashing. The fifth term is bonus received from the manufacturer when the delivery time is ahead of time. The sixth term means the crashing cost of supplier 1. The final term is the loss of supplier 1 when the disruption happens. The expressions of two suppliers' actual delivery time which obey exponential distribution, can be substituted into Eq. 3 and the equation is simplified as follows.

$$\begin{aligned}TC^d_{s_1}(t_c)=&\,\tfrac{1}{\lambda_1}p_1e^{-\lambda_1(T_1-k-t_a+t_c)}+h_1(T_1-k-t_a+t_c-\tfrac{1}{\lambda_1}\\ &+\tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k-t_a+t_c)}+\tfrac{1}{\lambda_2}e^{-\lambda_2T_2}-\tfrac{1}{\lambda_1+\lambda_2}e^{-\lambda_1(T_1-k-t_a+t_c)}e^{-\lambda_2T_2})\\ &-b_1(T_1-k-t_a+t_c+\tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k-t_a+t_c)}-\tfrac{1}{\lambda_1})+\gamma t_c+k\delta\end{aligned} \tag{4}$$

To obtain the value of t_c, take the first derivative of t_c and set the equation equal zero. Then the following equation can be obtained:

$$(p_1+h_1-b_1-\tfrac{h_1\lambda_1}{\lambda_1+\lambda_2}e^{-\lambda_2T_2})e^{-\lambda_1(t_c+T_1-k-t_a)}=h_1-b_1+\gamma \tag{5}$$

Therefore, under decentralized decision the optimal crashing time t_c of supplier 1 is:

$$t^d_c=\tfrac{1}{\lambda_1}\ln\frac{(p_1+h_1-b_1)(\lambda_1+\lambda_2)-h_1\lambda_1e^{-\lambda_2T_2}}{(h_1-b_1+\gamma)(\lambda_1+\lambda_2)}-(T_1-k-t_a) \tag{6}$$

If t^d_c in the above equation is no more than zero, then $t^d_c=0$ which means that supplier 1 will not crash the delivery time. Take the second derivative of t_c in Eq. 4, then:

$$\begin{aligned}\frac{\partial^2 TC^d_{s_1}}{\partial t_c^2} &= (p_1\lambda_1 - b_1\lambda_1 + h_1\lambda_1 - \tfrac{h_1\lambda_1^2}{\lambda_1+\lambda_2}e^{-\lambda_2 T_2})e^{-\lambda_1(t_c+T_1-k-t_a)} \\ &> (p_1\lambda_1 - b_1\lambda_1 + h_1\lambda_1 - \tfrac{h_1\lambda_1^2}{\lambda_1+\lambda_2})e^{-\lambda_1(t_c+T_1-k-t_a)} \\ &> (p_1\lambda_1 - b_1\lambda_1)e^{-\lambda_1(t_c+T_1-k-t_a)} > 0\end{aligned} \quad (7)$$

Consequencely, Tc_{s1} (t_c) is convex in t_c, so t^d_c is the optimal value of supplier 1 under decentralized decision.

The cost of supplier 2 and the manufacturer under decentralized decision are formulated and simplified as follows, respectively:

$$\begin{aligned}TC^d_{s_2} &= \tfrac{1}{\lambda_2}p_2 e^{-\lambda_2 T_2} + h_2(T_2 - \tfrac{1}{\lambda_2} + \tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} \\ &\quad + \tfrac{1}{\lambda_2}e^{-\lambda_2 T_2} - \tfrac{1}{\lambda_1+\lambda_2}e^{-\lambda_1(T_1-k+t_c-t_a)}e^{-\lambda_2 T_2}) \\ &\quad - b_2(T_2 + \tfrac{1}{\lambda_2}e^{-\lambda_2 T_2} - \tfrac{1}{\lambda_2})\end{aligned} \quad (8)$$

$$\begin{aligned}TC^d_m &= p_m(\tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} + \tfrac{1}{\lambda_2}e^{-\lambda_2 T_2} - \tfrac{1}{\lambda_1+\lambda_2}e^{-\lambda_1(T_1-k+t_c-t_a)}e^{-\lambda_2 T_2}) \\ &\quad - (p_1\tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} + p_2\tfrac{1}{\lambda_2}e^{-\lambda_2 T_2}) + b_1(T_1 - k + t_c - t_a \\ &\quad + \tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} - \tfrac{1}{\lambda_1}) + b_2(T_2 + \tfrac{1}{\lambda_2}e^{-\lambda_2 T_2} - \tfrac{1}{\lambda_2})\end{aligned} \quad (9)$$

OPTIMAL ANALYSIS AND CONTROL UNDER CENTRALIZED DECISION

As to centralized decision, the goal of the assembly system is to find the optimal crashing time t_c and the total cost of assembly system is:

$$\begin{aligned}TC^c_{sc}(t_c) = {} & h_1[\int_0^{T_1-k+t_c-t_a} f(t_1')(T_1 - k + t_c - t_a - t_1)dt_1' + \int_0^{T_1-k+t_c-t_a}\int_{T_2}^{\infty} f(t_1')g(t_2)(t_2 - T_2)dt_1'dt_2 \\ & + \int_{T_1-k+t_c-t_a}^{\infty}\int_{t_1'-T_1+k-t_c+t_a+T_2}^{\infty} f(t_1')g(t_2)(t_2 - T_2 + T_1 - k + t_c - t_a - t_1')dt_1'dt_2] \\ & + h_2[\int_0^{T_2} g(t_2)(T_2 - t_2)dt_2 + \int_0^{T_2}\int_{T_1-k+t_c}^{\infty} f(t_1')g(t_2)(t_1' - T_1 + k - t_c)dt_2dt_1' \\ & + \int_{T_2}^{\infty}\int_{t_2-T_2+T_1-k+t_c-t_a}^{\infty} f(t_1')g(t_2)(t_1' - T_1 + k - t_c + t_a + T_2 - t_2)dt_2dt_1'] \\ & + p_m[\int_{T_1-k+t_c-t_a}^{\infty}\int_0^{t_1'-T_1+k-t_c+t_a+T_2} f(t_1')g(t_2)(t_1' - T_1 + k - t_c + t_a)dt_1'dt_2 \\ & + \int_{T_2}^{\infty}\int_0^{t_2-T_2+T_1-k+t_c-t_a} f(t_1')g(t_2)(t_2 - T_2)dt_2dt_1'] + \gamma t_c + k\delta\end{aligned} \quad (10)$$

Where, the first and second term, respectively stand for inventory holding cost of supplier 1 and 2. The third term is the manufacturer's penalty cost. The forth term means the crashing cost and the fifth term is the loss of supplier 1 when the disruption happens. The expression of two suppliers' actual delivery time can be substituted into Eq. 10 and the equation is simplified as follows:

$$\begin{aligned}TC^c_{sc}(t_c) = {} & h_1(T_1 - k + t_c - t_a - \tfrac{1}{\lambda_1} + \tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} + \tfrac{1}{\lambda_2}e^{-\lambda_2 T_2} - \tfrac{1}{\lambda_1+\lambda_2}e^{-\lambda_1(T_1-k+t_c-t_a)}e^{-\lambda_2 T_2}) \\ & + h_2(T_2 - \tfrac{1}{\lambda_2} + \tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} + \tfrac{1}{\lambda_2}e^{-\lambda_2 T_2} - \tfrac{1}{\lambda_1+\lambda_2}e^{-\lambda_1(T_1-k+t_c-t_a)}e^{-\lambda_2 T_2}) \\ & + p_m(\tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} + \tfrac{1}{\lambda_2}e^{-\lambda_2 T_2} - \tfrac{1}{\lambda_1+\lambda_2}e^{-\lambda_1(T_1-k+t_c-t_a)}e^{-\lambda_2 T_2}) + \gamma t_c + k\gamma\end{aligned} \quad (11)$$

Take first derivative of t_c in Eq. 13 and set it equal zero, then we get:

$$[(h_1 + h_2 + p_m) - (h_1 + h_2 + p_m)\tfrac{\lambda_1}{\lambda_1+\lambda_2}e^{-\lambda_2 T_2}]e^{-\lambda_1(T_1-k+t_c-t_a)} = h_1 + \gamma \quad (12)$$

The above equation can be solved as follows:

$$t^c_c = \frac{1}{\lambda_1}\ln\frac{(h_1 + h_2 + p_m)[(\lambda_1 + \lambda_2)e^{\lambda_2 T_2} - \lambda_1]}{(h_1 + \gamma)(\lambda_1 + \lambda_2)e^{\lambda_2 T_2}} - (T_1 - k - t_a) \quad (13)$$

According to Eq. 15, if t^c_c is larger than k, let $t^c_c = k$ which means supplier 1 will crash the delivery time no more than k. Take second derivative of t_c in Eq. 11, then:

$$\frac{\partial^2 TC^c_{sc}(t_c)}{\partial t_c^2} = (h_1 + h_2 + p_m)\lambda_1(1 - \tfrac{\lambda_1^2}{\lambda_1+\lambda_2}e^{-\lambda_2 T_2})e^{-\lambda_1(T_1-k+t_c-t_a)} > 0 \quad (14)$$

Therefore, the total cost of assembly system is convex in t_c which can make the assembly system minimum under centralized decision.

THE COMPENSATION MECHANISM UNDER SUPPLY DISRUPTION

Since, $p_m > p_1$, then $t^c_c > t^d_c$ which can be explained that the manufacturer transfers a higher penalty cost to supplier1 under centralized decision than under decentralized decision. This means under centralized decision supplier 1 faces a larger penalty cost and therefore will spend a greater cost to crash the delivery time.

However, through the above analysis the crashing time t^c_c of supplier 1 is best for assembly system under disruption. To incentive the supplier 1 to crash more delivery time, the manufacturer will coordinate the assembly system. Here we design a collaborative mechanism. The manufacturer will pay compensation for supplier 1's crashing and the compensation coefficient per unit time is β. As to the cost saved, the three partners in assembly system can share the saving cost according to a certain agreement. Under this compensation mechanism the cost function of supplier 1 becomes:

$$\begin{aligned}TC^\beta_{s_1} = {} & \tfrac{1}{\lambda_1}p_1 e^{-\lambda_1(T_1-k+t_c-t_a)} + h_1(T_1 - k + t_c - t_a - \tfrac{1}{\lambda_1} + \tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} + \tfrac{1}{\lambda_2}e^{-\lambda_2 T_2} \\ & - \tfrac{1}{\lambda_1+\lambda_2}e^{-\lambda_1(T_1-k+t_c-t_a)}e^{-\lambda_2 T_2}) - b_1(T_1 - k + t_c - t_a + \tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} - \tfrac{1}{\lambda_1}) \\ & + (\gamma - \beta)t_c + k\gamma\end{aligned} \quad (15)$$

Take the fist derivative of t_c in Eq. 15 and let it be zero. Then the optimal t_c under compensation mechanism can be obtained. The optimal value of t_c under compensation mechanism is:

$$t^\beta_c = \frac{1}{\lambda_1}\ln\frac{(p_1 + h_1 - b_1)(\lambda_1 + \lambda_2) - h_1\lambda_1 e^{-\lambda_2 T_2}}{(h_1 - b_1 + \gamma - \beta)(\lambda_1 + \lambda_2)} - (T_1 - k - t_a) \quad (16)$$

Set $t^b_c = t^c_c$, the compensation coefficient β can be got. Then the conclusion can be drawn.

Proposition 1 If the supplier's delivery is disrupted, the manufacturer can take the compensation mechanism to coordinate the assembly system. The compensation coefficient β can be solved through $t^b_c = t^c_c$.

Under compensation mechanism, the cost function of supplier 2 is the same as under decentralized decision but the cost function of manufacturer has changed to:

$$\begin{aligned} TC^{\beta}_{m} &= p_m\left(\tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} + \tfrac{1}{\lambda_2}e^{-\lambda_2 T_2} - \tfrac{1}{\lambda_1+\lambda_2}e^{-\lambda_1(T_1-k+t_c-t_a)}e^{-\lambda_2 T_2}\right) \\ &\quad - \left(p_1\tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} + p_2\tfrac{1}{\lambda_2}e^{-\lambda_2 T_2}\right) + b_1\left(T_1 - k + t_c - t_a \right. \\ &\quad \left. + \tfrac{1}{\lambda_1}e^{-\lambda_1(T_1-k+t_c-t_a)} - \tfrac{1}{\lambda_1}\right) + b_2\left(T_2 + \tfrac{1}{\lambda_2}e^{-\lambda_2 T_2} - \tfrac{1}{\lambda_2}\right) + \beta t_c \end{aligned} \tag{17}$$

NUMERICAL ANALYSIS

To illustrate regulation effect of compensation effect in the previous section and disruption period t_a's influence on parameters of assembly system. The numerical analysis will be given in Table 1 and 2.

Related parameters are assumed as follows: $p_m = 50$, $p_1 = 10$, $p_8 = 8$, $h_1 = 5$, $h_2 = 4$, $\lambda_1 = 1/50$, $\lambda_2 = 1/60$, $k = 30$, $\gamma = 3$, $\delta = 9$ and the following result can be obtained.

From the above numerical analysis we can draw the following conclusions:

- Under compensation mechanism the total cost of assembly system equal the cost under centralized decision, while the crashing time is the same under these two situations. This indicates that compensation mechanism can coordinate the assembly system which can make the total cost under disruption optimal
- When t_a small, supplier 1 is will not determine to crash delivery time, because supplier 1's crashing is equivalent to extending the delivery time. However, when the disruption occurs, the two suppliers have produced for a period and at this time whether supplier 1 crashes the delivery time or not is a new decision. At this moment supplier 1 has known the delivery time of supplier 2 and the new delivery time under disruption will be smaller than the original. To avoid suppliers' laying off deliberately, the manufacturer should monitor the production of two suppliers dynamically. If the supplier lies off deliberately or for a long time, it should be definitely be punished. When production time t_a before disruption is larger than a certain value, supplier 1 will decide crashing. The crashing time is increasing with t_a, because supplier 1 wants to complete the rest time of delivery earlier than the original
- Under centralized decision, the optimal crashing time of supplier 1 increases with t_a at first. When t_a

Table 1: Comparison between decentralized decision and centralized decision

		Decentralized decision				Centralized decision	
t^a	t^d_c	TC^d_{s1}	TC^d_{s2}	TC^d_m	TC^d_{sc}	t^c_c	TC^c_{sc}
5	0	420.449	191.272	990.021	1601.744	11.499	1590.304
10	0	425.814	194.862	1009.014	1629.691	16.499	1605.304
15	0	432.233	1982.137	1032.143	1663.206	21.499	1620.304
20	0	439.817	203.213	1049.845	1702.876	26.499	1635.304
25	0	448.668	208.059	1092.599	1749.347	30	1650.486
30	0	458.983	213.414	1130.937	1803.335	30	1668.835
35	0	470.850	219.320	1175.446	1865.630	30	1691.774
40	0	484.455	225.873	1226.776	1937.105	30	1719.691
45	3.799	499.339	227.543	1240.194	1976.137	30	1753.206
50	8.799	514.339	227.543	1240.194	1982.137	30	1792.876
55	13.799	529.399	227.543	1240.194	1997.137	30	1839.347
60	18.799	544.399	227.543	1240.194	2012.137	30	1893.135

Table 2: Sensitivity analysis under compensation mechanism

	Compensation mechanism					
t^a	β	t^{β}_c	TC^{β}_{si}	TC^{β}_{s2}	TC^{β}_m	TC^{β}_{sc}
5	2.4170	11.499	418.284	184.259	987.759	1590.304
10	2.4170	16.499	421.197	184.259	999.846	1605.304
15	2.4170	21.499	424.111	184.259	1011.933	1620.304
20	2.4170	26.499	427.025	184.259	1024.019	1635.304
25	2.3710	30	431.356	185.085	1034.043	1650.486
30	2.2070	30	439.828	188.024	1040.982	1668.835
35	2.0250	30	449.681	191.272	1050.790	1691.744
40	1.8250	30	461.059	194.862	1063.769	1719.691
45	1.6030	30	474.125	198.829	1080.252	1753.206
50	1.3587	30	489.055	203.213	1100.607	1792.876
55	1.0881	30	506.044	208.059	1125.243	1839.347
60	0.7891	30	525.311	213.414	1154.609	1893.335

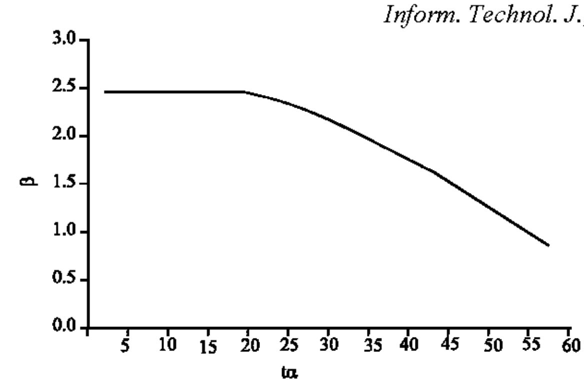

Fig. 4: Sensitivity of compensation coefficient to t_a

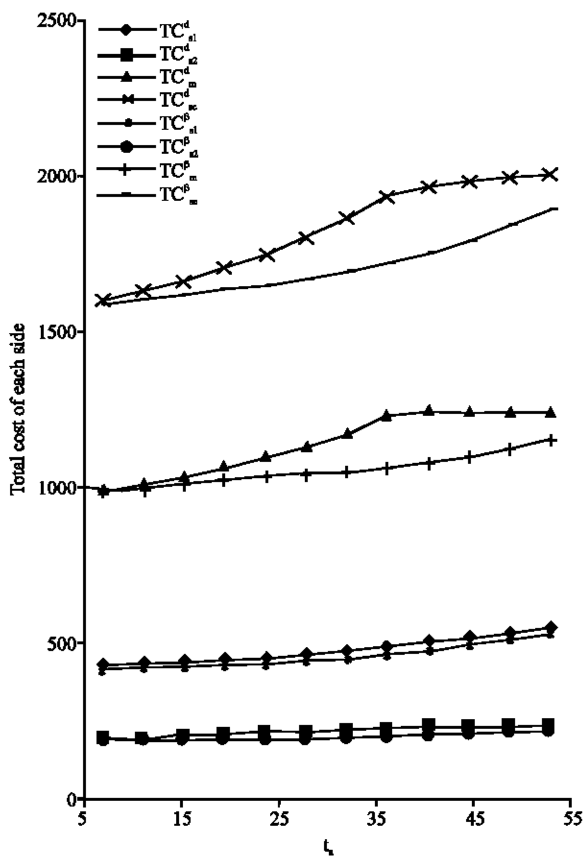

Fig. 5: The cost of each partner in assembly system influenced by t_a

excesses a certain value, the crashing time will equal the disruption time which means the later the disruption of supplier 1 occurs the greater harm the disruption will bring to assembly system

- The compensation coefficient β is decreasing with the postponement of the disruption (Fig. 4). From Fig. 4, we can clearly find out that compensation coefficient the manufacturer offers is decreasing with postponement of supplier 1's disruption. Thus, supplier 1 has a greater incentive to crash the delivery time and the manufacturer can reduce the compensation
- The disruption point of supplier 1 influences each side of supply chain as shown in Fig. 5

Figure 5 clearly shows that compared to decentralized decision under compensation mechanism the cost of two suppliers, the manufacturer and the assembly system are reduced which proves the compensation mechanism is effective. As t_a is increasing, the cost of each side in assembly system is increasing, indicating that the later the supplier 1's disruption occur the greater impact the disruption has on assembly system.

CONCLUSION

In this study, we formulate the coordination model under supply disruption and achieve the supply coordination with compensation mechanism. The model under decentralized decision and under centralized decision are analyzed and compared and the compensation mechanism is proposed to coordinate the supply chain. Numerical analysis shows the collaborative mechanism is effective. Besides, the result shows when t_a is small, supplier 1 will not determine to crash delivery time, because supplier 1 's crashing is equivalent to extending the delivery time. However, when the disruption occurs, the two suppliers have produced for a period and at this time whether supplier 1 crashes the delivery time or not is a new decision. At this moment supplier 1 has known the delivery time of supplier 2 and the new delivery time under disruption will be smaller than the original. To avoid suppliers' laying off deliberately, the manufacturer should monitor the production of two suppliers dynamically. If the supplier lies off deliberately or for a long time, it should be definitely be punished. Interestingly, when production time t_a before disruption is larger than a certain value, supplier 1 will decide crashing. The crashing time is increasing with t_a, because supplier 1 wants to complete the rest time of delivery earlier than the original.

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