

Coordinating Supply Chain Distribution in the Presence of Production Disruption Risks

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Abstract: *With the impacts of unexpected events, production processes of supply chain system may be forced to interrupt in a certain period, which may decrease the supply capacity of manufacturer to its retailers. This paper discusses methods to distribute the limited stock in case the production disruptions occur. To ascertain a reasonable replenish sequence and quantity after the production disruption, a production disruption-oriented supply chain distribution model is offered, which can be used to minimize the negative impact of production disruption to supply chain system. And then a constraint satisfaction optimization method is established to resolve the model. Finally, validity of the model is verified with an actual application in an air-conditioner factory in China.*

Keywords: *Emergency response, Production disruption, Supply chain distribution, Risk management*

1. Introduction

In recent years, so many unexpected events occur all over the world, such as earthquakes, tsunamis, bird flu, and blizzard freezing rain etc. (Sheffi Y., 2005; Pearson H., 2004). The experience of the 2008 Wenchuan, China earthquake shows that disasters continue to cause loss of human life, environment damage, disruption of infrastructure, and economic loss. In the late 1990s, both Nokia and Ericsson depended on the supply of chips for their mobile phones from Philips Electronics Inc. in New Mexico. In March 2000, a fire caused by lightning rendered Philips unable to supply the chips for several weeks. Adopting different disruption management approaches resulted in vastly different destinies for the two companies. Nokia gained 3% for its mobile phones global market share from 27 to 30% in 2000. However, Ericsson retreated from the phone handset production market in January 2001 with a loss of 1.68 billion dollars for its mobile phone division (Latour, 2001); Rio Tinto Alcan's Laterriere Works aluminium smelter in Quebec suffered a significant power outage July 6, 2010. After two electrical transformers failed, leaving the plant without the adequate energy required to continue operating at full capacity. As a result of the incidents, and as a safety precaution, one of Laterriere Works' two production lines has been suspended. The smelter is currently operating at half of its total capacity of 235,000 tonnes. Therefore, the disasters management is under close public scrutiny. Accompanying with unexpected incidents, sudden changes of demand information, supply disruption and production equipment unexpected damaged affected the operation of enterprises greatly. Compared with a single enterprise, supply chain system

becomes more complex, which faces more dynamic and uncertain environment.

Today, unexpected events in supply chain have drawn much attention of some scholars. And there exists a large body of literature related to sourcing strategies, risk management and decision-making under uncertainty. Brain Tomlin(2006) proved that in the special case in which the reliable supplier has no flexibility and the unreliable supplier has infinite capacity, a risk-neutral firm will pursue a single disruption-management strategy: mitigation by carrying inventory, mitigation by single-sourcing from the reliable supplier, or passive acceptance. Tagaras G and Vlachos D (2001) analyzed a periodic review inventory system with two replenishment modes in case of supply chain disruption. Chiang C (2001) studied the optimal order strategy with emergency order. Haisheng Yu, Amy Z.Zeng and Lidu Zhao (2009) evaluated the impacts of supply disruption risks on the choice between the famous single and dual sourcing methods in a two-stage supply chain with a non-stationary and price-sensitive demand. Hallikas and Vivolainen (2002) have found that a small customer structure change and a short lead time could result in supply chain risk and disruption, and furthermore, the relationship between the buyer and the supplier affects those risks and disruptions. Kleindorfer and Saad (2005) presented a supply chain risk framework called SAM, where "S" refers to specifying sources of risk and vulnerabilities, "A" means assessment, and "M" stands for mitigation. Chen, K. and Xiao, T. (2008) developed two coordination models of a supply chain consisting of one manufacturer, one dominant retailer and multiple fringe retailers to investigate how to coordinate the supply chain after demand disruption. Reay-Chen

Wang and Hsiao-Hua Fang (2000) studied a novel fuzzy linear programming method for solving the aggregate production planning problem.

Comparing with the impact of uncertainties among enterprises, uncertainty in the area of production systems of one supply chain is lack of study. Min Soo Suh, etc. (1998) studied the internal supply chain disruptions to production strategy, and proposed method of response planning process based on the constraints satisfied method, the core of which is operation compositor, including variable compositor and value compositor strategy. Taking into account that the response to a certain part of the production disruption may cause another part of the production be interrupted, Thomas Tsukada etc. (1993) proposed an intelligent resumption model, and used artificial intelligence technology to resolve the model. Xia et al. (2004) presented a general disruption management approach for a two-stage production and inventory control system.

For the emergencies occurred in production system, current study mostly focused on production restoring, and less study take notice of affections to retailers caused by the production disruption. In the complex and volatile market competition, all kinds of unexpected events could lead to production disruption, which may cause distributors and retailers facing a shortage risk. Unexpected events may have a major impact on manufacturers, and manufacturers have to adjust its sales and logistics plan (P. Dutta et al., 2005). If the distributors or retailers do not accept this adjustment, from a legal perspective, often does not receive compensation, main while, unable to meet market demand will bring a higher out-of-stock loss (Wang Xuping, et al., 2005). When both sides of the transaction have agreed to adjust the sales and logistics plan, the key problem becomes how to make scientific decisions to adjust the given distribution and logistics strategies (Lu Zhen, et al., 2003). Centering on this scientific problem, the paper established a supply chain distribution model in condition of production disruption occurs, and offered a constraint satisfaction optimization method, which can be used to minimize the negative impact caused by disruption to the production supply chain system.

The remainder of the paper is organized as follows. Section 2 contains prerequisites for modeling supply chain distribution problems, which provides some basic assumptions and problem descriptions. Section 3 presents and analyzes the distribution model in the presence of production disruption risks, which is based on two goals, one is profit maximization and the other is shortage cost minimization. Section 4 offers the decision-making process of constraints satisfaction, which includes the decision making rules and constraint satisfaction algorithm. A set of application of the distribution model in one China air-conditioner factory and discussions of the associated results are given in Section 5. Finally, the managerial implications of the research results, the limitations of the proposed model, and some possible future research directions are reported in Section 6.

2. Prerequisites for modeling supply chain distribution problems

In a typical supply chain environment, material flows through the system and changes form as it goes through various stages. These stages typically include the raw material supplier, the manufacturer, the distributor, the wholesaler, the retailer and finally the customer who receives the product. For convenience, this paper discusses a two-stage supply chain system consisting of one manufacturer and m retailers, and all the retailers facing certain demand. The manufacturer offers all retailers only one kind of product, and the unit production cost is c . Suppose the manufacturer receives orders from all retailers at the start point 0, and both transport time from the manufacturer to each retailer and cost associated with each retailer are constants. All retailers' sales cycle start from TS , and end after TE . After received orders, the manufacture begins preparing for production and logistics plan, and starts production. As the shortage of raw materials, machine malfunctions or other unexpected events, production disruption occurred between TI and TR , and $TI > TS$.

In this paper we assume that the manufacturer's productivity is a constant. Though the manufacturer is likely to raise productivity after production resuming from the disruption, but this does not affect the nature of the problem.

We consider the situation where the manufacturer is completely down and unable to satisfy all the m retailers demand when struck by unexpected events. For general, we suppose that the manufacturer begin replenishing to retailers after production disruption. If replenishment occurs before production disruption, the manufacturer has already offered some retailers full supply in accordance with pre-determined plan. And after the disruption, these retailers will be excluded during decision-making response.

Thus, retailers, supply quantity, and supply time constitutes a complete distribution strategy, which indicates when, who and how much to supply. And so, the main problem of the distribution strategy is how to rationally allocate the limited products. As production was suspended, the manufacturer can't meet all orders, and has to focus limited products to some retailers, which enhanced some retailer's profit on the loss of other's profit. Another problem is to decide the reasonable choice of shipping time. For increasing supply capacity, the manufacturer wishes to postpone supply. But for the transportation time and marketing period, it can not be postponed unlimited.

3. Distribution models and analyses

Essence of the supply chain management is to take the supply chain as a whole, and upgrade the whole supply chain competitive advantage in the method of overall optimization, thus ensuring the profitability of all the

enterprises. From this viewpoint, goals of the supply chain (one manufacturer and m retailers) that facing disruption is twofold: one is maximization of profit and the other is minimization of shortage cost.

3.1 Objective functions

The first goal is maximization of the supply chain profit. For analysis convenience, the paper introduces the concept of "replenishment compositor", which refers to the time sequence of the products shipped from the manufacturer to each retailer. For a supply chain has m retailers, there are $m!$ compositors. For example, suppose $m=3$, then there are 3 retailers, and the replenishment sequences will be $3!=6$, and suppose ϕ is the cluster of replenishment sequences, then

$$\phi = \left\{ \begin{array}{l} R_1, R_2, R_3; R_1, R_3, R_2; R_2, R_1, R_3; \\ R_2, R_3, R_1; R_3, R_1, R_2; R_3, R_2, R_1 \end{array} \right\}$$

Suppose R_{jk} ($j=1,2,\dots,M; k=1,2,\dots,M!$) is the j th retailer of the k th supply order and its cost is C_{jk} . Suppose, P_{jk} is the price in market and q_{jk} is the product quantity that R_{jk} received from the manufacturer. From the perspective of supply chain system, as transfer payments between manufacturer and retailers is not relevant to the decision-making, the first goal of the distribution decision-making model is,

$$\text{Max } PF = \sum_{j=1}^M (P_{jk} - C - C_{jk}) q_{jk} \quad (\forall k) \quad (1)$$

The second goal is minimization of shortage cost. We define the shortage cost as the opportunities loss in production and business activities, which is caused by failure to meet market demand. Shortage of product not only loses the current sales opportunities, but also leads to the loss of future opportunities. Shortage cost is essentially the opportunity cost, although it does not constitute the actual expenditure, it does bring negative impact to corporate image and reputation. Shortage of product may lead to consumers purchase other products, thus in the long-term perspective, it can affect the overall supply chain interests. Shortage cost reflects the degree of customer satisfaction in certain extent, the higher the cost of shortage, the lower the level of customer satisfaction. In the customer-lead market competition, pursuit minimization of shortage cost is getting more important, which means improvement of customer satisfaction.

We suppose D_{jk} is the market demand of R_{jk} (as mentioned above, R_{jk} is the j th retailer of the k th supply order). And if the manufacturer doesn't offer enough products, the unit shortage cost is S_{jk} . Then, the second goal of the distribution decision-making model is,

$$\text{Min } SA = \sum_{j=1}^M (D_{jk} - q_{jk}) S_{jk} \quad (\forall k) \quad (2)$$

Many scholars combine these two goals together and pursue the maximization of $(PF - SA)$ (Cachon, et al.,

2005; Guo Min, et al., 2002; Yu Hui, et al., 2005). But in the presence of production disruption risks, taking the importance of the shortage into account, decision makers do not just consider about $(PF - SA)$, but do consider about shortage cost SA . And so, in this paper we will set profit level and shortage cost as two separate targets to control.

3.2 Constraints of the model

Constraints in model (1) and (2) can be divided into four categories: resource constraints, time constraints, rational constraints and other constraints.

For production disruption, orders of each retailer can not be fully satisfied, which can be regarded as resource constraints. Suppose the start time of the manufacturer replenishing products to the R_{jk} retailer is t_{jk} . And on each t_{jk} , the supply quantity q_{jk} should satisfies the relationship,

$$q_{jk} \leq Q_S + v \left(T_I + \max \{ t_{jk} - T_R, 0 \} \right) - \sum_{d=1}^{j-1} q_{dk} \quad (3)$$

Note that in (3), v denotes the productivity. And $v \left(T_I + \max \{ t_{jk} - T_R, 0 \} \right)$ denotes the output between 0

and t_{jk} , and $\sum_{d=1}^{j-1} q_{dk}$ denotes the products amount replenished to retailers in the $(j-1)$ supply time ahead.

In case of production disruption, the manufacturer may wish to delay the supply in order to increase supply capacity, but because of the existence of schedule time, supply can not be delayed too late, otherwise manufacturer will miss the marketing, which is defined as time constraints in this paper. And the shipping sequences among each shipping time are dependent on each other. Suppose, TR_{jk} is the transport time from the manufacturer to retailer R_{jk} . Time constraints are as follows,

$$\begin{aligned} t_{jk} &\leq T_E - TR_{jk} \\ t_{ik} &\leq t_{(i+1)k} \quad i = 1, 2, \dots, M-1 \end{aligned} \quad (4)$$

We define the rational constraints as the inventory of each individual retailer shipped from manufacturer does not exceed the number of its original order, that is,

$$0 \leq q_{jk} \leq D_{jk} \quad (5)$$

Furthermore, decision maker may add some other constraints according to their demand. For example, they may require the shipping amount should up to one certain limitation to one important area, and so on.

4. Decision-making process of constraints satisfaction

In the presence of production disruption risks, the distribution decision-making of limited product stock is a multi-goal process, and the solution can only be a satisfied one, which is based on the decision-makers' preference. There may be a certain degree of conflict between the two objectives between profit level and

shortage cost, and often can not be optimal at the same time. If decision maker improve the goal of profit level, which may increase the shortage cost. Therefore, the ultimate decision-making is a satisfactory decision rather than optimal decision. In addition, different decision-maker has different preference. The same level of profit or shortage cost may be acceptable to some decision-makers, while others are considered to be unacceptable. In business practice, such preferences permeate the decision-making process, but the traditional optimization methods do not support the decision-makers preferred embodiment. Therefore, the constraint satisfactory method is suitable for resolving such issues.

According to the constraints satisfactory methods, in the portrait of decision-maker's satisfaction degree, first, we suppose the constraint cluster in distribution decision-making model is Θ , and in which the maximization and minimization of profit level PF and shortage cost SA are respectively $PF_{\max}, PF_{\min}, SA_{\max}$ and SA_{\min} . Second, we suppose the satisfactory function in the target range $[PF_{\max}, PF_{\min}]$ and $[SA_{\max}, SA_{\min}]$ is $\mu_{PF}(PF)$ and $\mu_{SA}(SA)$. For example, suppose PF_L, PF_U, SA_L, SA_U respectively represents the up bound and down bound of the profit and shortage cost function. For the preference of the decision maker, a ladder satisfaction function can be used as,

$$\mu_{PF}(PF) = \begin{cases} 0 & PF_{\min} \leq PF < PF_L \\ \frac{PF - PF_L}{PF_U - PF_L} & PF_L \leq PF \leq PF_U \\ 1 & PF_U < PF \leq PF_{\max} \end{cases} \quad (6)$$

$$\mu_{SA}(SA) = \begin{cases} 1 & SA_{\min} \leq SA < SA_L \\ \frac{SA_U - SA}{SA_U - SA_L} & SA_L \leq SA \leq SA_U \\ 0 & SA_U < SA \leq SA_{\max} \end{cases} \quad (7)$$

4.1 Decision-making rules

Under the conditions of production disruption, for the existence of association among the multi-objectives of the distribution model, we propose three decision-making rules, with combination of different decision-maker's preferences.

Rule 1: On the basis of both profit and shortage cost meets decision maker's satisfaction, pursuit maximization of shortage cost SA .

$$\begin{aligned} \max \quad & \mu_{SA}(SA) \\ \text{st.} \quad & \mu_{PF}(PF) \geq \bar{\mu}_{PF} \\ & \mu_{SA}(SA) \geq \bar{\mu}_{SA} \end{aligned} \quad (8)$$

Rule 2: On the basis of both profit and shortage cost meets decision maker's satisfaction, pursuit maximization of profit level PF .

$$\begin{aligned} \max \quad & \mu_{PF}(PF) \\ \text{st.} \quad & \mu_{PF}(PF) \geq \bar{\mu}_{PF} \\ & \mu_{SA}(SA) \geq \bar{\mu}_{SA} \end{aligned} \quad (9)$$

Rule 3: On the basis of both profit and shortage cost meets decision maker's satisfaction, searching by a certain way, such as integrated level of satisfaction SS is maximized.

$$\begin{aligned} \max \quad & SS = \alpha \mu_{PF}(PF) + (1 - \alpha) \mu_{SA}(SA) \\ \text{st.} \quad & \mu_{PF}(PF) \geq \bar{\mu}_{PF} \\ & \mu_{SA}(SA) \geq \bar{\mu}_{SA} \end{aligned} \quad (10)$$

Formula (8), (9) and (10) omitted the constraints set Θ . $\bar{\mu}_{PF}$ and $\bar{\mu}_{SA}$ respectively represents the satisfactory demand of two goals of decision maker's profit levels and shortages cost, and α is the weight of the profit target level.

4.2 Constraint satisfaction algorithm

Take rule 3 as an example, the constraint satisfaction algorithm can be designed as follows, and algorithm corresponding to rule 1, 2 can conduct similar research. Decision variables in the optimal model are k, q_{jk} and t_{jk} , and the optimal model is formed by formula (10) and constraints set Θ . Algorithm steps as follows,

- Step 1. Analyze the possible supply order, and total number is $M!$;
- Step 2. Set $k = 1, SS_{\max} = 0, Mark = 0$;
- Step 3. If $k > M!$, turn to step 7, or to the next step;
- Step 4. Take the k_{th} supply order, and initialize corresponding parameters;
- Step 5. For assured k , if the constraint satisfaction programming model formed by formula (9) and constraints set Θ can be solved, and the optimal value of objective function $SS^* > SS_{\max}$, then, set $k^* = k, q_j^* = q_{jk}, t_j^* = t_{jk}, Mark = 1$, and turn next step, or else, directly turn to the next step;
- Step 6. Set $k = k + 1$, and turn to step 3;
- Step 7. Output $k^*, q_j^*, t_j^*, SS_{\max}, Mark$, and end.

When the output $Mark = 0$, the algorithm does not have a feasible solution, which means the satisfaction degree is too high, and it should be appropriate to relaxed requirements, that is to say, $\bar{\mu}_{PF}, \bar{\mu}_{SA}$ should be reduced.

5. Application and discussion

5.1 Application of the model

Take one air-conditioner manufacturer in China as application. The sale of this factory shows the performance of a certain periodicity. Take the two-stage supply chain which includes this factory and 4 retailers for consideration, each retailer face different marketplace because of geographical dispersion. And parameters of each retailer as shown in table 1.

A certain model air-conditioner parts for the unit manufacturing is 35 Yuan per piece, and original inventory of this part is 200. Suppose retailers have issued orders at zero time, and this round of the sales cycle will begin after nine days, and sustained in two

| | | | | |
|-------------------------------|----------------|----------------|----------------|----------------|
| Item / retailer | R ₁ | R ₂ | R ₃ | R ₄ |
| Retail price (Yuan/piece) | 80 | 50 | 65 | 75 |
| shortage cost (Yuan/piece) | 10 | 15 | 8 | 12 |
| Order quantity (Piece) | 1100 | 1400 | 1500 | 1000 |
| transportation time (Day) | 4 | 2 | 3 | 1 |
| other cost /unit (Yuan/piece) | 8 | 4 | 6 | 2 |

Table 1. Basic parameters of each retailer

days. Productivity of the factory is 600 pieces per day. However, production disruption occurs in the second day due to sudden power breakdown, which caused production out of job for four days. Manufacturers have to re-distribute so as to minimize the loss of power failures. First, the distribution model is established in accordance with the above mentioned decision-making methods. After mathematic analysis, we can get the highest profit is 11690 and the minimum is 0. Meanwhile, the highest level of shortage cost is 56000 and the minimum is 9600. Second, decision-maker quest for the scheme with the highest synthesized satisfaction in the scope of profit satisfaction up to 0.8 and shortage cost satisfaction up to 0.95. Designated functions of the decision-makers are as follows,

$$\mu_{PF}(PF) = \begin{cases} 0 & 0 \leq PF < 95000 \\ \frac{PF - 95000}{20000} & 95000 \leq PF \leq 115000 \\ 1 & 115000 < PF \leq 116900 \end{cases}$$

$$\mu_{SA}(SA) = \begin{cases} 1 & 9600 \leq SA < 15000 \\ \frac{55000 - SA}{40000} & 15000 \leq SA \leq 55000 \\ 0 & 55000 < SA \leq 56000 \end{cases}$$

According to the decision of managers, we set $\alpha = 0.5$, and the optimal solution can be got as shown in table 2. Under this scheme, profit of the supply chain is 115000 Yuan with the satisfaction level is 1, and shortage cost is 16977 Yuan with the satisfaction level is 0.9506, and the synthesized satisfaction level is 0.9573.

5.2 Discussion and analysis

The above mentioned method is compared with other decision-making methods to illustrate its effectiveness in this part. Here only consider economic consequences, without considering the legal consequences, and we assume the manufacturer cancel all sales contracts unilaterally.

In the case discussed above, if the manufacturer cancels the contract of sale, supply chain system will to the bad, and shortage cost will achieve the maximum 56,000 Yuan, and the customer demand is not met at all. The method offered in this paper can effectively enhance the supply chain system profit levels and reduce costs in short supply. Reduction of the shortage cost shows that customer needs are better met, which reflects supply chain management objectives.

| | | | | |
|-----------------|----------------|----------------|----------------|----------------|
| Supply time | 5.5 | 7.7564 | 8.3333 | 10 |
| Retailer | R ₁ | R ₃ | R ₂ | R ₄ |
| Supply quantity | 1100 | 1353.8 | 346.15 | 1000 |

Table 2. Optimal solution of distribution

Suppose the manufacturer pursuit for the largest value of (PF-SA), as shown in most literature.

Using this method, the optimal solution is on the 5.5th, 8th, 8.3333th, 10th day begin replenishing its retailers, and the corresponding supply quantity separately is 1100, 1500, 200, and 1000 pieces. And the profit of the supply chain system is 116900, and the shortage cost is 18,000, then $PF - SA = 98900$. With the satisfaction degree is 0.925, which is lower than decision makers' expectation. Yet, according to the method offered in this paper, $PF - SA = 98023$ which is less than 98900 indeed. But the shortage cost is only 16977, that is to say, though (PF-SA) decreases 0.8868%, shortage cost reduces 5.6833%.

6. Conclusions

In recent years, frequent natural disasters and other emergencies brought about a serious impact to the production processes, which may interrupt production systems in a certain period and affect the supply capacity of downstream distributors. In market-oriented competition, customer loyalty and satisfaction and other factors caused more attention to enterprise decision makers. And out-of-stock enterprises will undoubtedly affect their own image and status, and further weaken its competitive advantage. In this paper, a supply chain distribution decision model is offered in condition of production disruption, which can help enterprise to determine reasonable supply order and quantity after production disruption so as to reduce the negative impact of production disruption. Finally, an application result of one air-conditioning enterprise in China demonstrates the validity of the model. Convenient for research, the paper only studied a two-stage supply chain system which includes one manufacturer and several retailers, and assume the retailers face certain demand. In future research, related issues in more complex multi-supply chain systems will be further explored.

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8. Appendix. List of notation and symbols used throughout the paper

| | |
|----------------|---------------------------------------------------------------------------------------------|
| m | the amount of retailers discussed in this paper |
| c | the unit production cost |
| TS | all retailers sales cycle start time |
| TE | all retailers sales cycle end time |
| TI | production disruption occurs time |
| TR | production disruption end time |
| v | the manufacturer's productivity |
| R_{jk} | the j th retailer of the k th supply order |
| C_{jk} | the cost of R_{jk} |
| P_{jk} | the price in the market |
| q_{jk} | the product quantity of R_{jk} |
| PF | the profit of the supply chain |
| D_{jk} | the market demand of R_{jk} |
| S_{jk} | the unit shortage cost |
| SA | the total amount of shortage cost |
| t_{jk} | start time of the manufacturer supplying products to the R_{jk} retailer after disruption |
| Q_s | the origin stock of products |
| qdk | the products amount of d^{th} retailer in k^{th} supply order |
| TR_{jk} | the transport time from the manufacturer to retailer R_{jk} |
| Θ | the constraint cluster in distribution model |
| PF_{\max} | maximization of profit |
| PF_{\min} | minimization of profit |
| SA_{\max} | maximization of shortage cost |
| SA_{\min} | minimization of shortage cost |
| $\mu_{PF}(PF)$ | the satisfactory function of PF |
| $\mu_{SA}(SA)$ | the satisfactory function of SA |
| PFL | the down bound of the profit |
| PFU | the up bound of the profit |
| SAL | the down bound of the shortage cost |
| SAU | the up bound of the shortage cost |
| μ_{PF} | the satisfactory demand of two goals of decision maker's profit levels |
| μ_{SA} | the satisfactory demand of two goals of decision maker's shortage cost |
| α | the weight of the profit target level |

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