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Research on Blood Supply Chain Optimization under Supply Unreliable and Stochastic Demand

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Abstract. This paper explores the problem of blood supply chain optimization under the double uncertainty of supply and demand, considers the impact of supply unreliability, demand difference and different inventory allocation methods on supply chain performance, and constructs a mathematical model of multi-cycle operation of blood supply chain. The blood supply chain system expiration rate under different strategy combinations was obtained through computer simulation optimization. Through the analysis of the results, it is found that the supply fluctuation has a greater impact on the performance of the supply chain. The performance adjustment effect of the distribution mode itself is small. Expiration due to short-term demand fluctuations is greater than the expiration rate caused by long-term demand fluctuations. Proposed a blood supply chain operation strategy for different supply environments.
Keywords. Unreliable supply, Demand difference, Distribution method, Blood supply chain.

1. Introduction

Blood is a special perishable product with a very short shelf life and high cost of shortage, its only source is the donation of people [1]. Due to the randomness of supply and demand and the asymmetry of information, the supply and demand in the supply chain often cannot be accurately matched. High stocks can guarantee supply, but it brings a very high risk of overdue and dampens the blood donation of blood donors [2]. How to protect supply and reduce expired waste has always been a key issue for blood supply chain research.

The general supply chain research is to minimize the cost as the optimization goal, and there are few studies to ensure the supply and reduce waste as the optimization goal [3]. However, once a blood shortage occurs, there will be a high cost of shortage, reducing expired waste and ensuring supply is one of the keys to blood supply chain optimization, which also makes the research results of many perishable products not applicable to the blood supply chain [4]. In recent years, many scholars have carried out research on the issues related to the blood supply chain, and most scholars have only paid attention to the unreliability of blood demand. Literature [5] pays attention to the random demand of blood. He aims to optimize hospital cost, out-of-stock level and expired level, and uses integer programming to study the optimal order level of blood inventory. Literature [6] describes the uncertain blood demand with Poisson distribution, and considers the possibility of alternative use between different blood types. The blood supply chain is studied by system simulation and heuristic algorithm. Literature [7] discussed a two-stage blood inventory model in a randomized environment and demonstrated the superiority of centralized control in the blood supply chain management process. Literature [8] studies the blood supply chain under unreliable blood demand and finds that the cooperation of members in the blood supply chain can greatly improve the efficiency of the blood supply chain. In recent years, many scholars have also paid attention to the randomness of blood supply. Such as Ramezanian [9] considered the impact of donation distance, advertising and other factors on the donor's blood donation behavior. They used the donor utility function to describe the donor's dynamic donation behavior, and based on this, built a blood supply chain network model. Literature [10] studied a blood supply chain planning model considering alternative use between different blood types under the dual uncertainty of supply and demand. Literature [11] used a normal distribution to characterize the randomness of supply, and explored the problem of blood supply chain optimization with blood transfer between hospitals and blood type replacement.

Because the patient's blood needs are random, medical surgery, natural disasters [12-13], etc. may bring huge and sudden blood demand. On the other side, the only source of blood is the donor's donation, and the donation behavior is highly subjective [14~16]. This makes blood supply chain optimization should consider both the uncertainty of supply and demand. However, most of the above articles only consider the randomness of blood demand, but few articles discuss the unreliability of supply.

Based on the premise of unreliable supply and age difference, this paper distinguishes the market characteristics of blood demand faced by each hospital, and carries out a simulation of 52 weeks (about a natural year) through MATLAB. The blood supply chain with two control methods, two distribution methods and one replenishment method were studied. The approximate optimal solution is obtained by genetic algorithm, and the optimal strategy combination that supply chain participants can adopt in the unreliable supply environment is proposed. The results show that unreliable supply makes blood supply chain management more difficult. In this case, centralized control is particularly effective; when supply is reliable, the difference in single-day demand fluctuations is more than the impact of one-week demand fluctuation on supply chain performance. Larger; the regulation of the distribution strategy itself is very weak, and in the case of large fluctuations in the supply chain, this regulation will have a negative impact.

2. Problem Description

This paper takes the blood center and three hospitals as the perishable product supply chain. In this supply chain, it is assumed that the size of the hospital is equivalent, that is, the expected total clinical blood demand for each hospital tends to be the same, but each hospital has different fluctuations in the clinical blood demand every day and every week. Assuming that the hospital's blood needs obey the Poisson distribution [6, 17], the average demand for each hospital per week is as follows:

- The 1st hospital: 27, 33, 34, 31, 34, 22, 21,
- The 2nd hospital: 25, 34, 27, 34, 28, 17, 19,
- The 3rd hospital: 22, 28, 29, 26, 37, 23, 24.

It can be seen from the average blood demand, the scale of the three hospitals is basically the same. However, the demand for the first hospital was relatively stable (the sum of the absolute mean difference in daily demand per week was the smallest = 26), and the second hospital had the biggest weekly fluctuations in demand (the sum of the absolute mean difference in daily demand per week = 42). However, compared with the third hospital, its daily demand fluctuations are relatively stable. The difference in average demand reflects the different characteristics of the markets served by the hospital. In general, the market characteristics faced by the three hospitals are shown in the table 1 below.

Table 1. Market characteristics of blood demand.

Hospital	Demand characteristics	Market characteristics
1	Daily demand is stable Weekly demand is stable	Demand is stable
2	Daily demand fluctuations are relatively large Large fluctuations in weekly demand	Short-term demand is relatively stable Long-term demand is extremely unstable
3	Large fluctuations in daily demand Weekly demand fluctuations are relatively large	Short-term demand is extremely unstable Long-term demand is relatively stable

The blood center supplies platelets to the three hospitals mentioned above. In this blood supply system, it takes a day for the blood center to complete the production and transportation process after receiving the order, and the stock allocation is performed according to the corresponding allocation strategy. Every day, the hospital conducts inventory counts, clears expired inventory, counts the shortage on the day, makes replenishment decisions through the maximum inventory strategy, and performs inventory updates. The inventory update steps of the blood center and the hospital are as follows: 1) After the demand for the day is satisfied, the remaining shelf life of the inventory is 1 day for the expired scrapping; 2) the remaining shelf life of all remaining stocks is reduced by 1 day; 3) the new arrival of the goods into the warehouse update. All members of the blood supply chain use the First in First Out outbound strategy [18].

3. Modeling

This paper constructs a mathematical model to more clearly describes the supply chain operation mode and evaluation method. The meanings of the indicators, parameters and variables involved in the model are shown in table 2:

Table 2. Nomenclature.

Subscripts	**Description**
t	Period T is the maximum planning horizon， $t=1,2,...,T$
i	$i=0$ stands for blood center and $i=1,2,...,N$ stands for hospitals
r	Residual shelf life of item on stock, $r=1,2,...,M$
$x_{i,r}^{t}$	The number of stock in Supply chain entity i in t period with residual shelf life of r days
$E_i(.)$	The expected demand of entity i
φ	The predetermined highest shortage rate
SS_i^t	The maximum stock of entity i in t period
Q_i^t	The ordering quantity of entity i in t period
S_i^t	The shortage quantity of entity i in t period
O_i^t	The outdate quantity of entity i in t period

$P=\{P_1,...,P_i,...,P_N\}$ Probability density function representing market demand compliance (pdf). D_i^t stands for the demand of hospital i in t period, $D^k=\{D_1^t,...,D_i^t,...,D_N^t\}$stands for the clinical demand for the hospital N in k period, $k=1,2,...,N$. The inventory status of every entities in the blood supply chain are described as $x^t=\{x_0^t,...,x_i^t,...,x_N^t\}$. Perishables are especially suitable for outbound using FIFO strategies [19~21]:

$$x_{i,r}^{t} = \begin{cases} (x_{i,r}^{t} - D_i^t)^+, r = 1 \\ \left(x_{i,r}^{t} - \left[D_i^t - \sum_{j=1}^{r-1} x_{i,j}^{t}\right]\right)^+, r > 1 \end{cases} \tag{1}$$

Due to imbalances in supply and demand, it may happen that existing stocks cannot meet demand. Given the initial inventory level of the first phase of each member of the entire supply chain system is $x^1=\{x_0^1,x_1^1,\ldots,x_N^1\}$, thus in period t, the shortage number and outdate number with the stock status is x_i^t can be shown as:

$$S_i^t(x_i^t) = \left[D_i^t - \sum_r x_{i,r}^t\right]^+, t = 0,1,\ldots,T$$
$$O_i^t(x_i^t) = \max\{x_{i,1}^t, 0\}, t = 0,1,\ldots,T \tag{2}$$

Thus, the shortage rate and outdate rate can be described as:

$$SR_i = \frac{\sum_{t=1}^{T} S_i^t(x_i^t)}{\sum_{t=1}^{T} D_i^t}, i = 0,1,\ldots,N$$
$$OR_i = \frac{\sum_{t=1}^{T} O_i^t(x_i^t)}{\sum_{t=1}^{T} Q_i^t}, i = 0,1,\ldots,N \tag{3}$$

The classic order-up-to level strategy is suitable for the blood supply chain to make replenishment decisions [22,23]. This paper assumes that all members of the supply chain use the order-up-to level strategy for replenishment. The strategy can be expressed as:

$$\text{if } IP_i^t < SS_i^t, then\ Q_i^t = SS_i^t - IP_i^t \tag{4}$$

In the allocation strategy, the blood center has two allocation strategies to choose from. The first strategy is to prioritize according to the order size, which is called the big order priority allocation strategy, and the second strategy is to give priority according to the hospital number. The ranking is called the hospital priority allocation strategy, and the hospital with a small serial number has a higher priority.

Finally, in terms of control strategy, this paper considers two supply chain strategies: centralized control and decentralized control. Both strategies aim to minimize the expiration rate within a certain out-of-stock range. Centralized control strategies to minimize the overall expiration rate of the supply chain system, and its mathematical model can be expressed as [17]:

$$F_{centralized} = min \sum_{i=0}^{N} \{E_p(OR_i)\}$$
$$s.t. max\{E_p(OR_i)\} \leq 1 - \varphi,\ \ i = 1,2,\ldots,N \tag{5}$$

The decentralized control strategy aims to minimize the expiration rate of individual supply chain members themselves, and the mathematical model can be expressed as [17]:

$$F_{centralized} = \sum_{i=0}^{N} min\{E_p(OR_i)\}$$
$$s.t. max\{E_p(OR_i)\} \leq 1 - \varphi,\ \ i = 1,2,\ldots,N \tag{6}$$

4. Simulation Optimization Results

In order to study the impact of supply environment on supply chain decision-making, this paper conducted a 52-week simulation of the perishable supply chain with different decision combinations in the environment of reliable supply and unreliable supply. Because the problem involved is solved in a large scale [24], this paper uses genetic algorithm to obtain the approximate optimal solution of the expected system expiration rate of each decision combination, and conducts comparative analysis.

4.1. *Supply Reliable*

Supply reliability means that the blood center can always produce according to the planned output and deliver orders on time, which is an ideal stable production state. When the size of the hospital is similar, the average value of each hospital's demand is similar each day. Therefore, when the demand for each order can be satisfied to a large extent, the weekly order quantity is similar.

Table 3. Simulation optimization results using decentralized control in a reliable supply environment.

	Supply chain entities				System
	1	2	3	0	
Big order priority					
OR	0.229049	0.253840	0.289398	0.000000	0.203287
SR	0.000101	0.001302	0.001165	0.000000	0.000406
Hospital priority					
OR	0.290550	0.253086	0.231652	0.000000	0.217191
SR	0.000907	0.000651	0.000000	0.000000	0.000252

The simulation optimization results taking decentralized control in reliable supply environment are shown in table 3. Because hospitals are similar in size, the difference in demand has less impact on the retailer's own expiration rate. When a large order-first allocation method is adopted, since it preferentially satisfies the order with the largest demand, it has a certain "on-demand allocation" adjustment function. In this case, the demand of the hospital directly reflects the state of clinical demand, which makes the demand environment faced by the hospital have a greater impact on its own expiration rate. The hospital with the lower fluctuation of demand in the market has the lowest, the expiration rate, and the hospital with the most fluctuations in single-day demand has the largest expiration rate. When hospital priority allocation is used, the principle of FIFO leads to hospitals with priority allocations always getting less than fresh stocks, so hospitals with higher priority always have higher expiration rates and higher priority. The hospital does not necessarily have the most urgent need for orders in the current period. In this case, the large order priority makes the old inventory transfer to a hospital with a larger demand and is quickly consumed, thereby reducing the system expiration rate.

Table 4. Simulation optimization results using centralized control in a reliable supply environment.

	Supply entities				System
	1	2	3	0	
Big order priority					
OR	0.066140	0.076071	0.085585	0.000000	0.037921
SR	0.000000	0.001627	0.002119	0.000000	0.000588
Hospital priority					
OR	0.081856	0.066947	0.047900	0.000000	0.032994
SR	0.000000	0.000002	0.001007	0.000000	0.000169

Centralized control can improve the performance of supply chain for every entity by integrating demand points, because the demand points are integrated the difference in demand between hospitals and hospitals is weakened, which reduces the role of large order allocations in adjusting the demand for a single demand point. In reliable supply environment, simulation optimization results under centralized control are shown in table 4. At the same time, the dynamics of priority allocation rights leads to Increased uncertainty. Therefore, under centralized control, the hospital's priority allocation strategy is better than the big order priority allocation strategy. Since the volatility of the sum of multiple demand points is less than the variability of the demand of each hospital, when the demand is uncertain, the different demand points are brought together for centralized control, and the expected demand of a hospital above the average level will be lower than that of other zero hospitals. The average expected demand can be offset [24]. Thus, Centralized control can always achieve better supply chain performance than decentralized control.

4.2. Supply Unreliable

In fact, due to factors such as blood collection process, blood separation process, donation by donors, etc., the production capacity of the blood center is always unreliable. This means that the blood center cannot guarantee that each production can be carried out according to the planned output, and the actual production may be below planned output, it may also be higher than planned output. This paper assumes that the actual supply is always between 95% and 105% of the planned supply and is randomly distributed according to the uniform distribution. The simulation optimization results under unreliable environment are shown in table 5-6, table 5 presents the results using decentralized control, table 6 shows the results taking centralized control.

Table 5. Simulation optimization results using decentralized control in an unreliable supply environment.

	Supply entities				System
	1	2	3	0	
Big order priority					
OR	0.424169	0.443870	0.415039	0.000014	0.393078
SR	0.001570	0.005285	0.002021	0.000000	0.001353
Hospital priority					
OR	0.418876	0.389321	0.349034	0.000003	0.317231
SR	0.001108	0.000217	0.000636	0.000000	0.000313

The big order priority strategy makes the hospital's priority to obtain platelets dynamic, and in the unreliable supply environment, the abnormal order is more likely to occur. At the same time, the dynamic nature of the hospital's ageing structure makes the order freshness extremely unreliable. Therefore, the big order priority strategy will intensify the uncertainty in the supply chain. In this case, the hospital's priority allocation method reduces the uncertainty in the supply chain with stable priority and predictable old inventory allocation, and achieves a lower system expiration rate. The stability of hospital priority allocation has also been confirmed in the study of Geng [24] et al.

Table 6. Simulation optimization results using centralized control in an unreliable environment.

	Supply entities				System
	1	2	3	0	
Big order priority					
OR	0.129114	0.113858	0.105584	0.000000	0.058329
SR	0.001266	0.001757	0.001388	0.000000	0.000685
Hospital priority					
OR	0.129594	0.115504	0.094494	0.000000	0.057007
SR	0.004183	0.001767	0.000000	0.000000	0.000906

Due to supply fluctuations, abnormal orders are generated. Therefore, the order quantity of a single period can no longer reflect the current demand. The big order priority allocation policy cannot reflect the adjustment effect of on-demand allocation, and can no longer reflect the difference of demand market, which makes the expired rate is no longer regular. When taking hospital priority allocation policy, due to the fixed priority and outbound principles, the order of old stock allocation is always determined. The higher the priority, the older stocks are obtained. Therefore, the hospital's expiration rate is still subject to priority. The higher the priority, the higher the rate of expiration.

5. Conclusions

The research results of this paper show that the demand market difference will affect the hospital's expiration rate. The impact of single-day demand fluctuation is greater than the one-week demand fluctuation, but the demand market difference will not affect the overall expiration rate of the supply chain. In addition, the adjustment of on-demand allocation with large order priority is very weak and will fail under uncertain supply conditions. Finally, centralized control integrates multiple demand points into one demand point for control, which reduces the difference between demand points. Therefore, centralized control can always achieve better supply chain performance than decentralized control.

This research can help decision makers make decisions in a dynamic environment, reduce blood shortage costs and expired losses, improve blood transfusion quality, and thus improve the service efficiency of medical health systems. However, this paper does not address the issue of blood supply chain operating costs, nor does it address issues such as batch supply, blood transport, and blood group replacement. The modeling ideas and optimization process of these problems are quite different from the paper. Therefore, considering the supply chain optimization problem based on transportation, inventory substitution and batch supply under the uncertain supply and demand environment will be an important direction for the author's follow-up research.

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