Resilience Optimization for Medical Device Distribution Networks Based on Node Failures

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Abstract: Our modern society comes to depend on large-scale supply chain networks to deliver resources to our homes and business in an efficient manner. However, there have been numerous examples where a local disturbance has led to the global failure of systems in recent years. Many researchers attempting to improve the resilience of logistics distribution systems to reduce the occurrence probability of its internal and external risks. The resilience of the medical device distribution networks is concerned with how to select distribution centers from a potential set so that the total cost is minimized and the resilience is maximized. In the paper, an optimization model for a resilient medical devices distribution network is proposed based on node failure probability, node failure costs and other factors. Furthermore, the validity and feasibility of the model is explained with an example.

Keywords — *Medical Device, Resilience, Distribution Center, Node Failure*

1. Introduction

Supply chain networks play a very important role in modern society. However, with market demand uncertainty and the constant emergence of unconventional emergencies, the global supply chain network becomes more and more fragile. Furthermore, traditional lean supply chain management continuously pursues low cost and zero inventory, putting supply chain in extreme tension. Once a key supply network is broken by a serious failure or terrorist attack, it is difficult to recover in a short time, supply costs rise sharply, and customer service levels decrease greatly. Therefore, it is important to construct resilient supply chain network with high level of self-recovery and improved the ability to recover normal supply chain operations when node failure risk occurs.

Resilience engineering, which has been widely researched [1-3], is an efficient way to analyze the security and stability of various complex systems [4]. In a supply chain network, the resilience can be understood as the ability to quickly recover and return to a stable state following a failure. A resilient supply chain network could reduce the probability of occurrence of its internal and external risks through its own pre-designed structure. Rosenkrantz et al. [5] proposed the concept of "structure-based resilience metrics" to quantify the resilience of nodes and edges in networks. Asha and Newth [6] proposed an evolutionary algorithm to evolve complex networks that are resilient to such cascading failure. Iakovou et al. [7] provided an up-to-date taxonomy of the risks that supply chains were exposed to along with the appropriate solutions that can be employed to improve their resiliency. Ratick et al. [8] used set cover location modeling as a method to determine the number of backup facilities to locate under varying cover, anticover, and complementary anticover distances. The model was applied to an example data set over 900 cities and towns in New England and New York. Wang et al. [9] developed a model based on the resilience evaluation approach to optimize the structure design of logistics networks. The evaluation criteria included the redundant resources, distributed suppliers and reachable delivery. Numerical examples have shown the efficiency and applicability of this model. Reed et al. [10] outlined a method to characterize the behavior of networked infrastructure for natural disaster events such as hurricanes and earthquakes. The method included resilience and interdependency measures. Furthermore, they also provided a brief calculation example using power delivery and telecommunications data collected post-landfall for Hurricane Katrina. Yan et al. [11] studied the emergency dispatch problem both when the network operates well and when one of the nodes fail, and developed an optimal model to minimize the total cost under the constraints of limited resources. Pettit et al. [12] proposed a conceptual framework to define

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resilience in terms of measurable variables. Gunasekarana et al. [13] developed a framework based on key factors/enablers that determine the resilience and competitiveness of small- or medium-sized enterprises. Cabral et al. [14] proposed an integrated LARG analytic network process (ANP) method to structure the lean, agile, flexible and green decision model of supply chains. Klibi et al. [15] developed various modeling approaches to design resilient supply networks for the location–transportation problem under uncertainty.

In the literatures referenced above, most of the researches examine the resilience of supply chains from a qualitative point of view, but there is hardly a structure design to research supply chain network resilience from a quantitative point of view. This paper utilizes the medical device supply chain as the background, and proposes an optimization model for a resilient medical devices distribution network based on the characteristics of the medical device distribution network and node failure probability.

The remainder of this paper is organized as follows: section 2 introduces the characteristics of medical device supply chain network; the optimization model of resilient medical device distribution network is proposed in section 3; the simulation and experimental results are presented in section 4; the conclusion and further remarks are provided in section 5.

2. The Medical Device Supply Chain Network

The medical device is a special medical product that is affected by several factors, including governmental rules and regulations and lean management. In the medical device supply chain distribution network, a supply disruption caused by network node failures could lead to incalculable consequences for ill patients. Therefore, this paper structures the resilient medical device distribution network, to reduce the losses and negative effects caused by network node failures.

2.1 The characteristics of the medical device supply chain network

In this subsection, the characteristics of a medical device supply chain network will be described. In comparison to ordinary consumer goods, the medical device distribution network has less hierarchy, high network resilience and high failure cost.

(1) Less network hierarchy

In the medical device distribution network, the quantity and types of products sold through retailers are few, and most medical devices are directly sold through hospitals. In contrast to medicine supply chain distribution, the medical device distribution network generally does not include wholesalers. Therefore, the hierarchy of the medical device supply chain distribution network is flatter, with mostly secondary networks.

(2) High network risk

Medical devices directly act on the human body, relate to people's health and safety, and typically require that their production conditions, transport apparatus and storage environment are germ-free and have consistent temperature and humidity. They also have more rigorous safety requirements for their transport, dispatching and storage. Compared with other devices, the network risk is greater.

In addition, medical devices have strict requirements for the specifications and types of products in use. Thus, product specificity is strong and substitutability is poor, and if the supply is disrupted, then it is difficult to find substitute products in a short time. Moreover, medical device are also strictly regulated by the Food and Drug Administration, the department of Health and other departments, and the rules and regulations require both the manufacturers of medical devices and the suppliers of the manufacturers to apply for approval. This approval process further increases the difficulties that the distribution network may face in utilizing outside resources when node failure occurs. Therefore, in comparison with other commodities, medical devices have a higher need for resilience.

(3) High failure cost

Medical devices are the important for people's health, and they have important influence on people's daily lives. When an external shock results in a supply disruption, this could cause patients' illness to become more serious, it could lead to death, bring incalculable losses, damage a government's reputation and international image, and be quite unfavorable to social stability. Therefore, the impact of a medical device distribution network failure is far greater than other ordinary consumer goods.

2.2 The resilience factors of the medical device distribution network

Distribution network resilience is generally influenced by several factors including risk management ability, network structure, information platform and governmental rules and regulations and so on. Network structure is the precondition for the existence of the medical device supply chain distribution network, it is the important material basis and physical support for the delivery flow of goods, information and fund, and it also plays the basic and decisive role in the distribution

network resilience. In the paper, we will try to improve the network resilience through the improvement of the medical device distribution network structure.

The resilience of a medical device distribution network is mainly influenced by the two factors of resilience investment cost and node failure cost, as shown Figure 1.

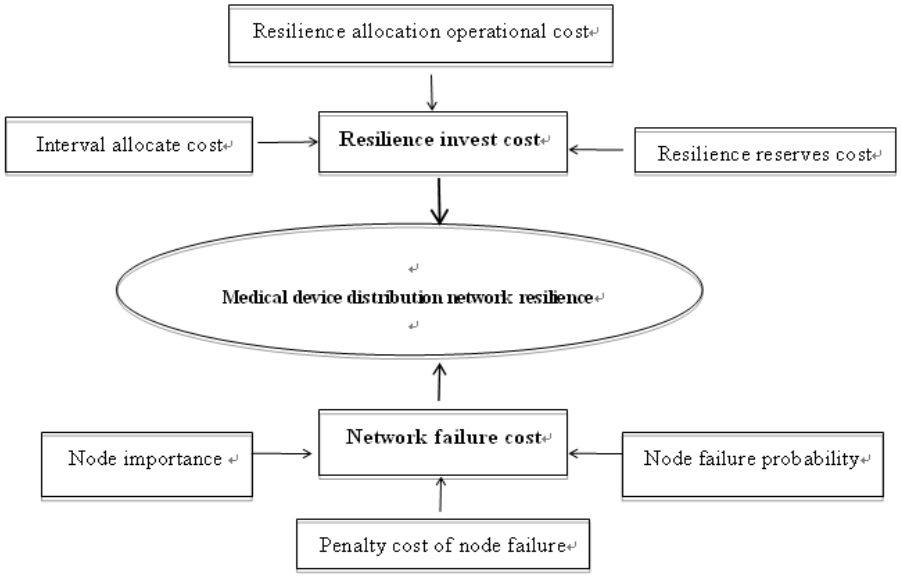

Figure 1. The resilience factors of medical device distribution network

The resilience investment cost is the cost of various measures taken to improve network resilience, such as the fixed investment expenses for newly established distribution centers and the storage cost caused by increasing inventory reserves. The resilience investment has direct influence on distribution network resilience; the more the resilience investment cost, the better the distribution network resilience. However, determining how to rationally assign the limited resources to maximize the improvement of network resilience under the constraint of the fixed resilience investment cost is particularly important.

Node failure cost is also called penalty cost, and it mainly includes customers' losses caused by failures and the transport expense resulting from interval allocation conducted when failure occurs. The whole failure cost of a distribution network directly relates to the node failure probability of the network; the lower the node failure probability, the better the network resilience.

3. Problem Model

3.1 Model assumption

(1) The fixed cost and unit operational cost of each candidate distribution centers are known.
(2) The failure probability of each candidate distribution center is known.
(3) If the distribution center does not fail, then each demand point should be supplied by one distribution center, and the demand quantity of each demand point is known.
(4) The unit transport rates from each manufacturer to the distribution center and from the distribution center to the demand point are known.
(5) The maximum capacity of the manufacturer and the maximum storage capacity of each distribution center are known.
(6) Under the condition of failure, each demand point has a resilience allocation from at least one distribution center.
(7) When failure occurs, the distribution center that supplies the resilience allocation for the demand point does not fail.
(8) When failure occurs, network has only single point failure.

3.2 Variable explanations

c: Unit product penalty cost caused by failure; mainly includes product shortage cost and social impact cost;

$I = (1, 2, \mathrm{L}\ n_1)$: Collection of manufacturers;

$J = (1, 2, \mathrm{L}\ , n_2)$: Collection of candidate distribution centers;

$K = (1, 2, \mathrm{L}\ , n_3)$: Collection of demand points, including hospitals, retailers, etc.;

q_k: Annual demand of demand point *k*;

q_{jk}: Supply quantity of distribution center *j* to demand point *k*;

d_{ij}: Transport distance from manufacturer *i* to candidate distribution center *j*;

w_{ij} : Transport quantity from manufacturer *i* to distribution center *j*;

d_{jk} : Transport distance from distribution center *j* to demand point *k*;

f_j: The fixed investment cost for selection of candidate distribution center *j*, including the expenses needed for a one-time investment for a newly established warehouse, purchase of equipments, etc.;

o_j : Unit operational expenses of candidate distribution center *j*;

c_{ij} : Unit transport fee from manufacturer *i* to candidate distribution center *j*;

c_{jk} : Unit transport fee from distribution center *j* to demand point *k*;

p_j : The failure probability of candidate distribution center *j*;

α_j : The influencing factors of candidate distribution center *j* for network failure cost;

I_{ij} : The resilience allocation quantity supplied by manufacturer *i* to distribution center *j*;

I_j : Resilience reserve quantity of distribution center *j*;

h_j : Unit storage expenses of candidate distribution center *j*;

O_{jk} : When the node fails, the resilience allocation quantity supplied by distribution center *j* to demand point *k*;

L_i : The maximum capacity of manufacturer *i*;

R_j : The maximum treatment capacity of distribution center *j*;

T^* : Resilience cost investment constraint;

x_j : 0, 1 variable expressing whether distribution center should be established at place *j* under the condition that the node does not fail. If established, then the value of is 1, otherwise it is 0;

y_{0ij} : 0, 1 variable expressing whether the reserve supply of candidate distribution center *j* is provided by manufacturer *i*. If yes, then the value is 1, and otherwise it is 0;

y_{1jk} : 0, 1 variable expressing whether the node does not fail if demand point *k* is assigned to candidate distribution center *j*. If yes, then the value is 1, and otherwise it is 0;

y_{2jk} : 0, 1 variable expressing whether the node does not fail if demand point *k* receives resilience demand allocation from candidate distribution center *j*. If yes, then the value is 1, and otherwise it is 0.

3.3 Problem model

$$\begin{aligned} Min\ F = & \sum_{i=1}^{I}\sum_{j=1}^{J}(1-p_j)c_{ij}d_{ij}w_{ij} + \sum_{j=1}^{J}\sum_{k=1}^{K}(1-p_j)c_{jk}d_{jk}q_{jk} \\ & + \sum_{j=1}^{J}(1-p_j)f_j x_j + \sum_{i=1}^{I}\sum_{j=1}^{J}(1-p_j)o_j w_{ij} \\ & + \sum_{i=1}^{I}\sum_{j=1}^{J}c_{ij}d_{ij}I_{ij} + \sum_{j=1}^{J}o_j I_j + \sum_{j=1}^{J}h_j I_j) \\ & + \sum_{j=1}^{J}\alpha_j p_j x_j \left(\sum_{k=1}^{K}c_{jk}d_{jk}O_{jk} + \sum_{k=1}^{K}c(q_k - \sum_{j=1}^{J}O_{jk}) \right) \end{aligned} \tag{1}$$

Subject to:

$$\sum_{i=1}^{I}\sum_{j=1}^{J}c_{ij}d_{ij}I_{ij} + \sum_{j=1}^{J}o_j I_j + \sum_{j=1}^{J}h_j I_j \le T^* \tag{2}$$

$$\sum_{j=1}^{J}y_{1jk} = 1, \quad \forall j \in J, k \in K \tag{3}$$

$$\sum_{k=1}^{K}q_{jk} \le M \cdot x_j, \quad \forall\, j \in J \tag{4}$$

$$\sum_{i=1}^{I}w_{ij} \le M \cdot x_j, \quad \forall\, j \in J \tag{5}$$

$$q_{jk} \le M \cdot y_{1jk}, \quad \forall\, j \in J, k \in K \tag{6}$$

$$\sum_{k=1}^{K}(q_{jk} + O_{jk}) \le R_j, \forall\, j \in J \tag{7}$$

$$\sum_{j=1}^{J}(w_{ij} + I_{ij}) \le L_i\ , \quad \forall i \in I \tag{8}$$

$$\sum_{i=1}^{I}w_{ij} = \sum_{k=1}^{K}q_{jk}, \ \forall\, j \in J \tag{9}$$

$$\sum_{j=1}^{J}q_{jk} = q_k, \forall k \in K \tag{10}$$

$$\sum_{j=1}^{J}O_{jk} \le q_k, \forall k \in K \tag{11}$$

$$\sum_{k=1}^{K} O_{jk} \le M \cdot x_j, \quad \forall j \in J \tag{12}$$

$$O_{jk} \le M \cdot y_{2jk}, \forall j \in J, k \in K \tag{13}$$

$$I_j \le M \cdot x_j, \forall j \in J \tag{14}$$

$$y_{0ij} \le x_j, \forall i \in I, j \in J \tag{15}$$

$$y_{1jk} \le x_j, \forall j \in J, k \in K \tag{16}$$

$$y_{2jk} \le x_j, \forall j \in J, k \in K \tag{17}$$

$$\sum_{i=1}^{I} I_{ij} = I_j, \forall j \in J \tag{18}$$

$$\sum_{k=1}^{K} O_{jk} \le I_j, \quad \forall j \in J \tag{19}$$

$$\sum_{i=1}^{I} I_{ij} \le M \cdot x_j, \forall j \in J \tag{20}$$

$$I_{ij} \le M \cdot y_{0ij}, \forall i \in I, j \in J \tag{21}$$

$$x_j, y_{0ij}, y_{1jk}, y_{2jk} \in \{0,1\}, \ \forall i \in I, \forall j \in J, \forall k \in K \tag{22}$$

$$w_{ij}, q_{jk}, I_j, I_{ij}, O_{jk} \ge 0, \quad \forall i \in I, \forall j \in J, \forall k \in K \tag{23}$$

In the above formulation, the objective function Eq. (1) represents the total cost. There are three aspects: (1) The normal operational cost of the medical device distribution network, which mainly includes transport expense, the fixed investment expense and operational expense of the distribution center; (2) The resilience cost caused by the resilience measures taken, including the establishment of resilience for the demand point and the distribution center interval emergency allocation when node fails. In the paper, the resilience cost mainly includes the inward transport cost, operational cost and inventory cost caused by the distribution center increasing goods reserves; (3) The failure cost caused by the factors of transport cost and sales losses resulting from interval allocation when the node fails.

Constraint Eq. (2) is the resilience investment constraint. Constraint Eq. (3) represents the unique assignment of a distribution center to a demand customer. Constraints Eq. (4)-(6) represent that the distribution center can service the demand customer only when the distribution center has been established. Constraints Eq. (7)-(8) are the capacity constraints for distribution center and the manufacturer, respectively. Constraints Eq. (9)-(10) represent the balance of supply and demand when the node does not fail. Constraint Eq. (11) represents dispatching constraints when the distribution network node fails. Constraints Eq. (12)-(13) represent that the distribution center could not provide the resilience allocation to any demand customer if the distribution center is selected. Constraints Eq. (14)-(21) express the balance constraints of resilience allocation. Constraint Eq. (22) imposes the integrality restriction on the decision variables $x_j, y_{0ij}, y_{1jk}, y_{2jk}$. Constraint Eq. (23) imposes the non-negativity restriction on decision variables $w_{ij}, q_{jk}, I_j, I_{ij}, O_{jk}$.

4. Numerical Examples

4.1 The example description

This section will give an example to show the application of the model. Suppose a large medical device manufacturer annually produces 3.50 million boxes medical device, and the market price of each box is 800 RMB. To meet the demand of the 39 market warehouses k_1-k_{39}, the manufacturer plans to select and establish regional warehouses among 11 candidate regional warehouses in China. Meanwhile, to improve the distribution network resilience, the manufacturer prepare to invest 10 million RMB in resilience costs and confirms the resilience reserves and resilience dispatching plan of each regional warehouse in the event that the node fails. Each candidate regional warehouse's fixed construction expenses, unit operational expenses, maximum capacity, unit reserve cost, and failure probability are known, as shown in Table 1. The transport distance, unit transport rate and the influencing factor of each candidate regional warehouse are shown in Table 2.

4.2 Results analysis

The distribution network resilience model is the mixed-integer linear programming model. In the paper, we will use Lingo to solve the model. The corresponding results are shown in Table 3.

Table 1. *Candidate regional warehouse's construction expenses, failure probability and unit operational expenses*

Candidate regional warehouse	Failure probability	Fixed cost (10 thousand RMB)	Unit operational expenses (RMB/Box)	Maximum capacity (10 thousand boxes)	Unit inventory expenses (RMB/Box)
J_1	0.20	270	1.24	54	0.21
J_2	0.25	80	1.32	46.1	0.22
J_3	0.31	120	1.5	32	0.25
J_4	0.22	220	4.1	58	0.68
J_5	0.28	70	2.03	46	0.34
J_6	0.25	170	2.41	52	0.40
J_7	0.26	90	2.37	49	0.40
J_8	0.24	100	2.88	32	0.48
J_9	0.30	150	3.05	36	0.51
J_{10}	0.25	90	0.38	50	0.06
J_{11}	0.27	60	1.2	38	0.20

Table 2. *Transport distance, transport rate and influencing factor*

Candidate regional warehouse	α_j	Production area	
		Transport rate (RMB/Box/km)	Transport distance (km)
J_1	1.0522	0.0030	950
J_2	1.0894	0.0036	1565
J_3	1.0560	0.0036	896
J_4	1.0833	0.0028	1055
J_5	1.1412	0.0045	1462
J_6	1.1985	0.0036	2446
J_7	1.1354	0.0036	2498
J_8	1.0729	0.0036	1580
J_9	1.0669	0.0036	823
J_{10}	1.0948	0.0036	549
J_{11}	1.1268	0.0036	1075

Table 3. Site selection and each warehouse's resilience reserves

J_j	I_j	Covering range
J_1	1396	k_3(36343), k_4(40595), k_5(44191), k_8(69218), k_{10}(70943), k_{11}(49378), k_{12}(827), k_{13}(30834), k_{14}(14072), k_{15}(19798), k_{20}(14062), k_{24}(66790), k_{28}(3302),

		k_{31}(2202), k_{36}(23313), k_{39}(52736)
J_2	293777	k_6(96994), k_7(46763), k_{29}(8464), k_{30}(15002)
J_4	3991	k_2(8778), k_{16}(85568), k_{17}(57905), k_{18}(60977), K_{19}(50418), k_{21}(5661), k_{22}(5071), k_{23}(102956), k_{25}(6928), k_{26}(42265), k_{34}(37505), k_{35}(38025), k_{37}(23180), k_{38}(50772)
J_8	5402	k_1(148322), k_9(56718), k_{27}(48971), k_{32}(4953), k_{33}((55634)

From Table 3, it is clear that four regional distribution centers are selected, namely J_1, J_2, J_4 and J_8. In the paper, I_j indicates the resilience reserves of each regional warehouse. For example, the reserves value I_4 of regional warehouse J_4 is 3991; the covering range is the number of the market warehouse covered by the regional warehouse, figures in brackets show the supply quantity supplied by the regional warehouse to the market warehouse under normal conditions. For instance, for regional warehouse J_8, the covered market warehouses are K_1, K_9, K_{27}, K_{32} and K_{33}, and the supply quantity are 148322, 56718, 48971, 4953 and 55634, respectively. Furthermore, the normal supply quantities, resilience reserves and allocation plans of the regional warehouse are shown in Table 4.

Table 4. Regional warehouse's normal supply quantity, resilience reserves and allocation

(i, j)	W_{ij}	I_j	O_{jk}
J_1	538604	1396	k_1(1396)
J_2	167223	293777	K_2 (8788), k_3 (27833), k_5 (44191), k_6 (96994), k_7 (46763), k_8 (69218)
J_4	576009	3991	k_{16}(3991)
J_8	314598	5402	K_{33}(5402)

From Table 4, it is clear that the network could only meet the demand of some market demand customers under the constraint of resilience cost. If the resilience cost is increased, it could meet the demand of more demand customers.

5. Conclusions

Rising volatility and uncertainty in global supply chains is causing traditional supply chain management models to break down. The resilience of SCM is one of the most important factors when node failure risk occurs, and has been extensively researched in recent years. Medical devices are indispensable, and constructing a distribution network with resilience is important to improve medical device distribution and protect people's lives and health.

In this paper, we first analyzed the main characteristics of the medical device distribution network and generalize the corresponding resilience factors. Then, we proposed a distribution network resilience model based on the node failure probability, node failure costs and other factors. Finally, the simulation and experimental results demonstrated the validity and feasibility of the model.

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