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Defining and measuring the network flexibility of humanitarian supply chains

Citation for published version (APA):

Baharmand, H., Comes, T., & Lauras, M. (2019). Defining and measuring the network flexibility of humanitarian supply chains: insights from the 2015 Nepal earthquake. *Annals of Operations Research*, *283*(1-2), 961-1000. https://doi.org/10.1007/s10479-017-2713-y

Document status and date:
Published: 01/12/2019

DOI:
10.1007/s10479-017-2713-y

Document Version:
Publisher's PDF, also known as Version of record

Document license:
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Please check the document version of this publication:

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Download date: 14 May. 2024

Annals of Operations Research (2019) 283:1551–1572
https://doi.org/10.1007/s10479-018-03127-5

S.I.: APPLICATIONS OF OR IN DISASTER RELIEF OPERATIONS, PART II

Optimization of humanitarian relief supply chain reliability: a case study of the Ya'an earthquake

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Abstract
This article seeks to propose a mathematical method to optimize the reliability of the humanitarian relief supply chain. Reliability and cost are both important in response to the disasters. To optimize the reliability of humanitarian relief supply chain and to find a trade-off between the reliability and cost, this article establishes a reliability integrated optimization model for the humanitarian relief supply chain and investigates the methods for optimizing the coordination between flow quantity and unit reliability, optimizes the allocation of reliability for each unit, to optimize the total reliability and cost of the humanitarian relief supply chain. To make the results of this article more applicable, this article applies a case study of the Ya'an earthquake to the built model and subsequently proves the related conclusions subsequently. These theoretical results can be used to improve the disaster operations efficiency of the humanitarian relief supply in the crisis state, achieve a win–win situation between the total reliability and cost.

Keywords Supply chain · Optimization model · Humanitarian relief · Reliability

1 Introduction

Natural disasters have affected lives, properties and economies at different scales over the past decades. For instance, the Sichuan Earthquake affected more than 40 million people and destroyed 4.5 million houses (Zhang and Chen 2016). With increasing concerns over the possibility of natural disasters, emergency managers are looking into ways to mitigate

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the impacts of disasters. Therefore, a timely and efficient disaster response supply chain is critical for successful disaster operations. Planning for relief supplies and response operations have largely been the concern of emergency management agencies. The supply chains which provide relief supplies after a disaster are called humanitarian relief supply chains (Zokaee et al. 2016).

Seen as one of the effective measures to mitigate disaster impacts, the humanitarian relief supply chain has attracted considerable attention. The humanitarian relief supply chain is complicated by the dynamics, risks and uncertainties of the disasters and operations, which makes it particularly difficult to establish measures of effectiveness for logistic functions (Thomas 2002). Additionally, humanitarian relief supply chains are generally much less efficient than commercial supply chains for many reasons, among them being the short duration and the frequent changes and unpredictability in supply and demand. For disaster operations, in the previous studies, time is often more critical than cost in making decisions, which is particularly early in the deployment of logistics and supply chain support of operations (Miman and Pohl 2008). Therefore, the likelihood of having the right supplies as needed is a more important measure of the effectiveness for humanitarian relief supply systems.

Under severe disaster situations, deficiency of supplies may have direct consequences. Recent research on humanitarian relief has put great emphasis on issues that provide a more reliable, efficient logistic and supply chain (Hamedi et al. 2012). A reliable humanitarian supply chain plays an important role in coping with dynamic emergency demand, uncertain supplies demand, and uncertain transportation conditions (Zhang 2012). Humanitarian relief supply chain reliability is defined as, the ability of the humanitarian relief supply chain to meet the needs of emergency facilities, distribution etc. in the specified time and conditions, or as the probability of that the complete system functions when an unexpected event occurs (Thomas 2002; Zhang 2012). Disasters are extremely destructive and unpredictable. Moreover, some natural disasters continue during disaster operations or cause new disasters, thus forcing the disaster operations to be developed under adverse natural conditions. For instance, a strong earthquake strikes in an instant but aftershocks can produce new damages. In such conditions the operation has to be developed with uncertainty about the damage in the supply chain. A way to model this uncertainty is through reliability analysis (Vitoriano et al. 2011). If the humanitarian relief supply chain is not highly reliable, supply disruptions often occur during or after disasters (Ukkusuri and Yushimito 2008). A supply disruption could dramatically increase social costs not only endangering life but also exacerbating supply delays. In addition, humanitarian relief needs to collect and produce adequate relief supplies in a short period of time (e.g., 72 h of gold), thus leading to a large great increase in the demand for emergency production. As a result, the capacity of the humanitarian relief supply chain will be near the peak, supply chain reliability will fall sharply, and supply shortages will inevitably occur (An et al. 2015).

However, while a large body of the most recent research is focused on the commercial supply chain, little attention has been focused on the humanitarian response problem during and after disasters. (Miman and Pohl 2008). The work presented in this present article is a new focus in the area of disaster operations. The objectives of commercial supply chain reliability are to maximize profits and to seek cost reductions; however, the objectives of the humanitarian relief supply chain reliability are to maximize the relief supplies and minimize the disaster losses (Thomas 2002). A few studies have focused on the reliability of the disaster operations where ensuring mission success is far more important than the cost (Gong et al. 2012; Miman and Pohl 2008). Although the analysis of the reliability of the humanitarian relief supply chain is of great importance, the improving reliability will bring about increasing costs. In situations where the government responsible for disaster operations is interested in a higher level of reliability they must sacrifice cost (Ghezavati et al. 2015), but the key question is by how much. Hence, the trade-off between reliability and cost is an important decision (Yildiz et al. 2016). Additionally, when the total reliability reaches a large value, increasing the unit reliability or budgeted costs always does not always significantly increase the total reliability. However, it significantly increases the cost, leading to the waste of resources, in this situation, the structure of the supply chain may contribute more significantly to reliability, the other key question that remains is when the structure will contribute more than the budget and unit reliability (Bertok et al. 2012). Therefore, this article aims to provide a reliable humanitarian relief supply chain model to address the uncertainty of demand, supply, and cost parameters. Thus, the reliability optimization models are proposed considering three emergency mobilization strategies. This article further integrates the three strategies and proposes the supply chain reliability integrated optimization model called SCRIOM. In addition, this article explores the relationship between the total reliability and the unit reliability and proposes a trade-off between total reliability and cost. By rationally optimizing the budget input and the unit reliability allocation, the cost decreases and the total reliability of the supply chain increases.

The rest of this article is organized as follows. Section 2 briefly reviews literature. Section 3 presents the supply chain reliability integrated optimization model (SCRIOM). Section 4 discusses a case study. Section 5 presents the research conclusions.

2 Literature review

The humanitarian relief supply chain is the key to disaster responses (Abidi et al. 2014). Recently, studies related to the humanitarian relief supply chain have received profound attention. Some studies have focused on measuring and managing the performance of the humanitarian relief supply chain (Beamon and Balcik 2008; Wang et al. 2016). Other studies are focused on the study of resilience (Elluru et al. 2017; Kaur and Singh 2016), sustainability (Kunz and Gold 2017; Papadopoulos et al. 2017) and robustness (Chen et al. 2015; Jabbarzadeh et al. 2014). In the last years, a large number of scientific contributions have been made to the optimization of humanitarian relief supply chain. Charles and Lauras (2011) proposed a conceptual modelling approach based on enterprise modelling methodologies, the proposed approach aided in optimizing the formal expression of a humanitarian supply chain. Tayal and Singh (2017) presented mathematical formulation for multi objective stochastic dynamic facility layout problem and optimized it using simulated annealing and chaotic simulated annealing. Zokaee et al. (2016) presented a robust three-level relief chain optimization model consisting of suppliers, potential relief distribution centers, and affected areas to address the uncertainty associated with some important parameters, such as demand.

Reliability is important to the supply chain. Recently, the study of supply chain reliability has witnessed a significant growth (Xiao and Qi 2016). Several researchers focused on the reliability evaluation of supply chain (Hsu and Li 2011; Lin et al. 2016). Some researchers optimized the reliability of supply chain or logistics (Pasandideh et al. 2015; Taki et al. 2016). Having a reliable humanitarian relief supply chain is critical. However, an understanding of reliability optimization in response to disasters is limited. In the limited studies. Kumar and Havey (2013) used the method of the effect of fault model and critical analysis to assess the reliability of the disaster supply chain system. Miman and Pohl (2008) provided a preliminary analysis of the use of risk and reliability tools for analyzing contingency logistics supply chains. Xu et al. (2015) constructed an evaluation model of disaster supply chain reliability to improve the disaster supply chain reliability under uncertain conditions.

Nonlinear programming is adopted to address the problem of optimization and the objective function in the presence of equality and inequality constrains. Nonlinear programming has been frequently used in the domain of supply chain (Badri et al. 2013; Ahmadi-Javid and Hoseinpour 2015). During the last decade, there was a growing interest using nonlinear programming to solve the optimization of humanitarian relief supply chain. Balcik et al. (2008) developed a mixed integer programming model for the relief supplies supply to minimize the total cost. Vitoriano et al. (2011) used the method of Goal programming to proposes the multi-rules for humanitarian relief distribution and established the multi-rules optimization model. Bozorgi-Amiri et al. (2012) proposed a mixed integer nonlinear programming model, which reduced the deviation between disaster supplies transportation total expected cost and the actual cost.

3 The theory of reliability of the humanitarian relief supply chain

3.1 Reliability optimization model modelling base

3.1.1 Objective function

The humanitarian relief supply chain aims to meet the disaster demand, so that the total shortage of emergency supplies is minimized. The objective function is shown in Eq. (3.1).

$$Min\Delta d, \quad \Delta d = d - f_n \tag{3.1}$$

Δd represents the total shortage of relief supplies that humanitarian relief logistics can't meet, and f_n represents the total number of supplies that reach each demand center.

3.1.2 Constraints

Due to limited resources, production capacity, etc., there are many constraints in the humanitarian relief supply chain.

1. Capacity constraint. Each unit within the limited time has a capacity limit for production and deployment. Considering the resource constraints of the components in the supply chain, it should be able to get the upper limit of its production capacity.
2. Supply balance constraint considering the bullwhip effect. The quantity of resources that the upstream enterprise provides to the downstream enterprise should not be lower than the quantity demand of the subordinate enterprise, which is the supply balance constraint. The bullwhip effect can't be completely eliminated. Therefore, bullwhip effect should be taken into account.
3. Total cost constraint. This article makes the total operating cost less than the upper limit of mobilization budget. This article uses the total cost constraint as a control means of economy. If the unit cost of a component is represented by $C(R)$, the flow provided by the unit is represented by f, and the unit cost of this unit can be represented by $C(R) \cdot f$. For example, the total operation cost constraint for a three-level supply chain of more than one raw material supplies can be expressed as follows:

Table 1 The implication of mathematical notations in Eq. (3.2)

Mathematical notation	Mathematical implication
$\sum_{n\in N}\sum_{k\in K}\sum_{i\in I} C_{S_nM_k} f^i_{S_nM_k}$	Cost of suppliers to manufacturers
$\sum_{k\in K}\sum_{t\in T}\sum_{p\in P} C_{M_kD_t} f^P_{M_kD_t}$	Cost of manufacturers to distribution areas
$\sum_{t\in T}\sum_{p\in P} C_{D_t} f^P_{D_t}$	Cost of disaster contingency areas to demand areas
N	Total number of suppliers
K	Total number of supplies
I	Total number of raw supplies
T	Total number of demand centers
P	Total number of relief supplies
$C_{S_nM_k}$	Unit cost from supplier S_n to material M_k
$C_{M_kD_t}$	Unit cost from material M_k to demand center D_t
$C_{M_kD_t}$	Unit cost from demand center D_t to demand areas
$\bar{C}$	Budget ceiling of the supply chain operating cost

$$\sum_{n\in N}\sum_{k\in K}\sum_{i\in I} C_{S_nM_k} f^i_{S_nM_k} + \sum_{k\in K}\sum_{t\in T}\sum_{p\in P} C_{M_kD_t} f^P_{M_kD_t} + \sum_{t\in T}\sum_{p\in P} C_{D_t} f^P_{D_t} \le \bar{C} \tag{3.2}$$

The left of the inequality represents the total cost of the three-level supply chain (Table 1).

4. Supply chain reliability constraint. The humanitarian relief supply chain requires a minimum of system reliability. If R_s represents the total reliability and $\bar{R}$ represents the low limit of reliability, then the reliability constraint is expressed as follows:

$$R_s \ge \bar{R} \tag{3.3}$$

3.2 Supply chain reliability optimization model without the emergency mobilization strategy

Considering the supply chain of a single relief supplies P, the supply chain reliability optimization model without emergency mobilization strategies can be expressed by Eqs. (3.4–3.10).

$$Min \Delta d \tag{3.4}$$

$$s.t. \sum_{k\in K} f^i_{S_nM_k} \le \bar{f}^i_{S_n}, \sum_{t\in T} f^P_{M_kD_t} \le \bar{f}^P_{M_k}, f^P_{D_t} \le \bar{f}^P_{D_t} \tag{3.5}$$

$$\sum_{k\in K}\sum_{t\in T} f^P_{M_kD_t} \ge \sum_{t\in T} \alpha_p f^P_{D_t}, \sum_{n\in N}\sum_{k\in K} f^i_{S_nM_k} \ge \sum_{k\in K}\sum_{t\in T} \alpha_i \lambda_{ip} f^P_{M_kD_t} \tag{3.6}$$

$$\sum_{n\in N}\sum_{k\in K}\sum_{i\in I} C_{S_nM_k} f^i_{S_nM_k} + \sum_{k\in K}\sum_{t\in T}\sum_{p\in P} C_{M_kD_t} f^P_{M_kD_t} + \sum_{t\in T}\sum_{p\in P} C_{D_t} f^P_{D_t} \le \bar{C} \tag{3.7}$$

$$R_s \ge \bar{R} \tag{3.8}$$

$$\Delta d = d^p - \sum_{t\in T} f^P_{D_t} \tag{3.9}$$

Table 2 The implication of the mathematical notations in Eqs. (3.4–3.10)

Mathematical notation	Mathematical implication
$f^{i}_{S_n M_k}$	Total number of raw supplies i provided by supplier S_n to manufacturer M_k
$\bar{f}^{i}_{S_n}$	Upper limit of the production capacity for raw supplies i provided by supplier S_n
$f^{p}_{M_k D_t}$	Total number of P provided by manufacturers M_k to the disaster area D_t
$\bar{f}^{p}_{M_k}$	Upper limit of the production capacity of P manufactured by manufacturers M_k
$f^{p}_{D_t}$	Total number of P in the disaster area D_t
$\bar{f}^{P}_{D_t}$	Upper limit of the capacity of P allocated by the disaster area D_t
d^{p}	Total demand for P by disaster points that is responsible for all demand areas
α_p	Expanded coefficient based on the demand forecast considering the security when the disaster area order P from manufacturers
λ_{ip}	Consumption of raw supplies i when manufacturing one unit of P
α_i	Expanded coefficient based on the demand forecast when manufacturers order raw supplies i

$$0 < R_s < 1 \tag{3.10}$$

In the model, the constraint conditions are the production capacity constraint (3.5), the supply balance constraint considering the bullwhip effect (3.6), the total cost constraint (3.7) and the minimal reliability constraint (3.8) (Table 2). Because the total cost and its reliability are interrelated, in theory, the total cost is an increasing function with respect to reliability. This article assumes the existence of a function between the costs of each enterprise and its reliability as shown in formula (3.11). a_{ij},b_{ij} represent the parameters of the supply chain constitutional unit $[i,j]$.

$$C_{ij}(R_{ij}) = b_{ij} - a_{ij}\ln(1 - R_{ij}) \tag{3.11}$$

After establishing the model under normal circumstances, this article will establish the model in an extreme case, and observe the results of the model, to prove the validity of the model.

Consider a simple supply chain that consists of one supplier, one manufacturer and one disaster area. The supply chain reliability optimization model can be represented as follows:

$$Min\Delta d$$

$$s.t.\ f^{i}_{SM} \le \bar{f}^{i}_{S},\ f^{p}_{MD} \le \bar{f}^{p}_{M},\ f^{p}_{D} \le \bar{f}^{p}_{D}$$

$$f^{p}_{MD} \ge f^{p}_{D},\ f^{i}_{SM} \ge f^{p}_{MD}$$

$$C(R_{SM}) + C(R_{MD}) + C(R_{D}) \le \bar{C}$$

$$R_{SM} * R_{MD} * R_{D} \ge \bar{R}$$

$$\Delta d = d^{p} - f^{p}_{D}$$

$$0 < R_{SM}, R_{MD}, R_D < 1$$

The following assumes two extreme cases. When the disaster demand is 0, there is no mobilization budget. The flow of each unit is 0, the reliability is 0, the result meets the reality. When disaster demand is infinity, the mobilization budget should also be infinity. This outcome means the unlimited budget, obviously, the flow of each unit will reach the upper limit of its supply ability, the result also meets the reality. In addition, it is easy to obtain from the model, as the minimum reliability limit increases, the operating cost increases. Thus, this model is valid.

3.3 Supply chain reliability optimization model with emergency mobilization strategies

This article analyzes three emergency mobilization strategies of humanitarian relief supply chain from micro-level: raw material buffer inventory strategy, additional production strategy, and relief supply reserve strategy. Then, this article provides three supply chain reliability optimization models based on the three respective emergency mobilization strategies.

3.3.1 Relief supply reserve strategy supply chain reliability optimization model

For the optimization model that introduces relief supply reserve strategy, it needs to have the following modifications from the basic model. First, due to the addition behavior of transporting supplies reserves, the supplies supply to the disaster area D will increase by f^p_{eD}, which represents the total reserves of supplies P that can be transported to the disaster area D. Second, the supply chain structure will change, thus the algorithm of the supply chain system reliability will change. Third, increasing the relief supply reserves will result in the increase of the total supply chain cost. Obviously, the cost and the number of relief supply reserves are positively correlated, and positively correlated with reliability, Therefore, if h^p_{eD} represents the unit inventory cost of relief supplies P, the supply chain operating cost of relief supplies P can be calculated, according to (3.12).

$$\begin{aligned}&\sum_{n\in N}\sum_{t\in T}\sum_{i\in I} C_{s_nM_k} f^i_{s_nM_k}+\sum_{k\in K}\sum_{t\in T}\sum_{p\in P} C_{M_kD_t} f^p_{M_kD_t}+\sum_{k\in K}\sum_{p\in P} C_{D_t} f^p_{D_t}\\&+\sum_{t\in T}\sum_{p\in P} h^p_{eD_t} f^p_{eD_t} C(R^p_{eD_t}) \le \bar{C}\end{aligned} \tag{3.12}$$

In reality, the unit inventory cost h_{ij} generally increases with the amount of storage. This article uses the staircase function (3.13) to express the inventory cost. Figure 1 shows the unit inventory cost function of relief reserve supplies.

$$h_{ij}=\begin{cases}h_{1,ij},\ 0<f_{ij}<f_{1,ij}\\ h_{2,ij},\ f_{1,ij}<f_{ij}<f_{2,ij}\\ h_{3,ij},\ f_{2,ij}<f_{ij}<f_{3,ij}\end{cases} \tag{3.13}$$

Through the above description, relief supply reserve strategy supply chain reliability optimization model is expressed by formula (3.14).

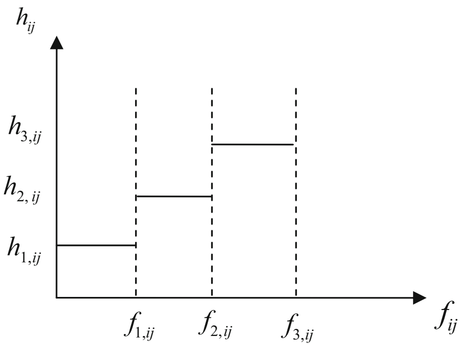

Fig. 1 Unit inventory cost function of relief reserve supplies

$$
\begin{aligned}
& Min\Delta d \\
& s.t.\ \sum_{k\in K} f^{i}_{S_nM_k} \le f^{i}_{S_n}, \sum_{t\in T} f^{p}_{M_kD_t} \le \bar{f}^{p}_{M_k}, f^{p}_{D_t} \le \bar{f}^{p}_{D_t} \\
& \sum_{k\in K}\sum_{t\in T} f^{p}_{M_kD_t} + \sum_{t\in T} f^{p}_{eD_t} \ge \sum_{t\in T}\alpha_p f^{p}_{D_t}, \sum_{n\in N}\sum_{k\in K} f^{i}_{S_nM_k} \ge \sum_{k\in K}\sum_{t\in T}\alpha_i\lambda_\varphi f^{p}_{M_kD_t} \\
& \sum_{n\in N}\sum_{t\in T}\sum_{i\in I} C_{s_nM_k} f^{i}_{s_nM_k} + \sum_{k\in K}\sum_{t\in T}\sum_{p\in P} C_{M_kD_t} f^{p}_{M_kD_t} + \sum_{k\in K}\sum_{p\in P} C_{D_t} f^{p}_{D_t} \\
& \quad + \sum_{t\in T}\sum_{p\in P} h^{p}_{eD_t} f^{p}_{eD_t} C(R^{p}_{eD_t}) \le \bar{C} \\
& R_s \ge \bar{R} \\
& \Delta d = d^{p} - \sum_{t\in T} f^{p}_{D_t} \\
& 0 < R_s < 1
\end{aligned}
\tag{3.14}
$$

3.3.2 Additional production strategy supply chain reliability optimization model

For the optimization model that introduces additional production strategy, it needs to include the following modifications from the basic model. First, the relief supplies supplied to the disaster area D will be increased by $\sum_{k\in K} f^{p}_{u_kD}$, which $\sum_{k\in K} f^{p}_{u_kD}$ represents total number of relief supplies P supplied by all manufacturing units who are involved in the additional production. Second, enterprises may adopt the method of increasing the working hours of employees and employing temporary workers to increase the production capacity of the enterprises. In this case, the added value of the production capacity is denoted by $\bar{f}^{p}_{u_kD}$. Obviously, the added value is very limited. Third, the reliability algorithm of the entire supply chain system will also change. Fourth, additional production will result in the increase of the total supply chain cost. The cost and the amount of additional production are positively correlated, and the cost is positive correlation with the reliability. Therefore, if $C^{p}_{u_kD}$ represents unit production cost of relief supplies P, the supply chain operating cost of relief supplies P can be calculated by formula (3.15).

$$\begin{aligned} C_s = &\sum_{n\in N}\sum_{k\in K}\sum_{i\in I} C_{s_nM_k} f^i_{s_nM_k} + \sum_{k\in K}\sum_{t\in T}\sum_{p\in P} C_{M_kD_t} f^p_{M_kD_t} + \sum_{t\in T}\sum_{p\in P} C_{D_t} f^p_{D_t} \\ &+ \sum_{k\in K}\sum_{t\in T}\sum_{p\in P} f^p_{u_kD_t} C^p_{u_kD_t} \end{aligned} \tag{3.15}$$

$$C^p_{u_kD_t} = [b_{M_kD_t} - a_{M_kD_t} * \ln(1 - R^p_{u_kD_t})] * \gamma \tag{3.16}$$

Then the additional production strategy supply chain reliability optimization model can be expressed by formula (3.17).

$$\begin{aligned} &Min \Delta d \\ &s.t. \; \sum_{k\in K} f^i_{S_nM_k} \le \bar{f}^i_{S_n}, \sum_{t\in T}(f^p_{M_kD_t} + f^p_{u_kD_t}) \le \bar{f}^p_{M_k} + \bar{f}^p_{u_k}, f^p_{D_t} \le \bar{f}^p_{D_t} \\ &\sum_{k\in K}\sum_{t\in T}(f^p_{M_kD_t} + f^p_{u_kD_t}) \ge \sum_{t\in T}\alpha_p f^p_{D_t}, \sum_{n\in N}\sum_{k\in K} f^i_{s_nM_k} \ge \sum_{k\in K}\sum_{t\in T}\alpha_i\lambda_{ip}(f^p_{M_kD_t} + f^p_{u_kD_t}) \\ &\sum_{n\in N}\sum_{k\in K}\sum_{i\in I} C_{s_nM_k} f^i_{s_nM_k} + \sum_{k\in K}\sum_{t\in T}\sum_{p\in P} C_{M_kD_t} f^p_{M_kD_t} + \sum_{t\in T}\sum_{p\in P} C_{D_t} f^p_{D_t} \\ &\quad + \sum_{k\in K}\sum_{t\in T}\sum_{p\in P} f^p_{u_kD_t} C^p_{u_kD_t} \le \bar{C} \\ &R_s \ge \bar{R} \\ &\Delta d = d^p - \sum_{t\in T} f^p_{D_t} \\ &0 < R_s < 1 \end{aligned} \tag{3.17}$$

3.3.3 Raw material buffer inventory strategy supply chain reliability optimization model

For the optimization model that introduces raw material buffer inventory strategy, it needs to incorporate the following modifications from the basic model. First, for the constraint condition of supply capacity, it's limited for any suppliers to establish a buffer inventory. The upper limit value of the ability can be expressed as $\bar{f}^l_{e_n}$, and the upper limit value may change with the supplier's original inventory, which is equal to $\beta * \bar{f}^l_{s_n}$, where $0 < \beta < 1$. Second, the reliability algorithm of the entire supply chain system will change. Third, with the introduction of raw material buffer inventory, the supply balance constraint between supplier and manufacturer under the bullwhip effect will change. Fourth, Raw material buffer inventory will result in the increase of the total supply chain cost, in which the cost and the reserve quantity of raw supplies are positively correlated, and the cost has positive correlation with the reliability. Therefore, if $C_{e_nM_k}$ represents unit inventory cost of raw material buffer inventory, it can calculate the supply chain operating cost C_s of relief supplies P using the formula (3.18).

$$\begin{aligned} C_s = &\sum_{n\in N}\sum_{k\in K}\sum_{i\in I} C_{s_nM_k} f^i_{s_nM_k} + \sum_{k\in K}\sum_{t\in T}\sum_{p\in P} C_{M_kD_t} f^p_{M_kD_t} + \sum_{t\in T}\sum_{p\in P} C_{D_t} f^p_{D_t} \\ &+ \sum_{n\in N}\sum_{k\in K}\sum_{i\in I} C_{e_nM_k} f^i_{e_nM_k} \end{aligned} \tag{3.18}$$

$C_{e_nM_k} = h_{e_nM_k}[b_{e_nM_k} - a_{e_nM_k} \ln(1 - R_{e_nM_k})]$, $h_{e_nM_k}$ is a staircase function, and $h_{e_nM_k}$ increases with the increase of raw material buffer inventory. The value of h can be determined by total number of raw material buffer inventory from the supplier.

Then, the raw material buffer inventory strategy supply chain reliability optimization model can be expressed by formula (3.19).

$$
\begin{aligned}
& Min\Delta d \\
& s.t.\ \sum_{k\in K} f^i_{S_nM_k} \le \bar{f}^i_{S_n},\ \sum_{k\in K} f^i_{e_nM_k} \le \bar{f}^i_{e_n},\ \sum_{k\in K} f^p_{M_kD_t} \le \bar{f}^p_{M_k},\ f^p_{D_t} \le \bar{f}^p_{D_t} \\
& \sum_{k\in K}\sum_{t\in T} f^p_{M_kD_t} \ge \sum_{t\in T} \alpha_p f^p_{D_t},\ \sum_{n\in N}\sum_{k\in K} (f^i_{s_nM_k} + f^i_{e_nM_k}) \ge \sum_{k\in K}\sum_{t\in T} \alpha_i \lambda_{ip} f^p_{M_kD_t} \\
& C_s = \sum_{n\in N}\sum_{k\in K}\sum_{i\in I} C_{s_nM_k} f^i_{s_nM_k} + \sum_{k\in K}\sum_{t\in T}\sum_{p\in P} C_{M_kD_t} f^p_{M_kD_t} + \sum_{t\in T}\sum_{p\in P} C_{D_t} f^p_{D_t} \\
& \quad + \sum_{n\in N}\sum_{k\in K}\sum_{i\in I} C_{e_nM_k} f^i_{e_nM_k} \le \bar{C} \\
& R_s \ge \bar{R} \\
& \Delta d = d^p - \sum_{t\in T} f^p_{D_t} \\
& 0 < R_s < 1
\end{aligned}
\tag{3.19}
$$

3.4 Supply chain reliability integrated optimization model

In the previous sections, supply chain reliability optimization models based on three emergency mobilization strategies is provided. These three strategies separately correspond to the supply link, manufacturing link and emergency distribution link in the supply chain. However, these three strategies are not used alone, instead, the appropriate strategies will be taken in each link of the supply chain from the perspective of different risk prevention strategies. Therefore, this section will integrate these three strategies and establishes the supply chain reliability integrated optimization model (SCRIOM).

3.4.1 Objective function and constraint conditions

The objective function is to minimize the deviation between the number of supplies supplied and the forecasted number of supplies demanded. Taking the supplies P as an example, the formula can be expressed as follows:

$$Min\Delta d = d^p - \sum_{t\in T} f^p_{D_t}$$

For the constraint condition of production capacity, in the SCRIOM, it needs to add the following constraints, as shown in formula (3.20). The left sides of the inequalities are the flow supplied by raw material buffer inventory, additional production and relief supply reserve, and the right sides are the corresponding supply capacity limit.

$$\sum_{k\in K} f^i_{e_nM_k} \le \bar{f}^i_{e_n},\ f^p_{u_kD_t} \le \bar{f}^p_{u_k},\ \sum_{t\in T} f^p_{eD_t} \le \bar{f}^p_{eD_t} \tag{3.20}$$

For the constraint condition of supply balance constraint that considers the bullwhip effect, the constraint is shown in formula (3.21). $f^{i}_{e_n M_k}$ represents the output flow in the raw material buffer inventory, $f^{p}_{u_k D_t}$ represents the material flow of additional production transported to transit point, $f^{p}_{eD_t}$ represents output flow in relief supply reserve.

$$\sum_{n\in N}\sum_{k\in K}(f^{i}_{S_n M_k}+f^{i}_{e_n M_k})\geq\sum_{k\in K}\sum_{t\in T}\alpha_i\lambda_{ip}f^{p}_{M_k D_t},\ \sum_{k\in K}\sum_{t\in T}(f^{p}_{M_k D_t}+f^{p}_{u_k D_t})$$
$$+\sum_{t\in T}f^{p}_{eD_t}\geq\sum_{t\in T}\alpha_p f^{p}_{D_t} \tag{3.21}$$

For the constraint condition of operating cost, the constraint condition is added as shown in formula (3.22) based on the basic model. $C_{e_n M_k}$ and C_{eD_t} are cost functions which are proportional to the unit reliability. $h^{i}_{e_n M_k}$ and $h^{p}_{eD_t}$ are unit inventory costs of raw material buffer inventory and relief supply reserve respectively. The cost of additional production is expressed as $\gamma(\gamma > 1)$, which has multiple relationships with the cost of normal production.

$$\sum_{n\in N}\sum_{k\in K}\sum_{i\in I}h^{i}_{e_n M_k}f^{i}_{e_n M_k}C_{e_n M_k}+\sum_{k\in K}\sum_{t\in T}\sum_{p\in P}f^{p}_{u_k D_t}C^{p}_{u_k D_t}+\sum_{t\in T}\sum_{p\in P}h^{p}_{eD_t}f^{p}_{eD_t}C^{p}_{eD_t} \tag{3.22}$$

3.4.2 Creation of the integration optimization model

The SCRIOM can be expressed as formula (3.23). The objective function of this model is still to minimize the number of stockouts. The constraint conditions are the production capacity constraint, supply balance constraint that considers the bullwhip effect, the cost budget constraint and the reliability constraint.

$$Min\Delta d$$
$$s.t.\ \sum_{k\in K}f^{i}_{S_n M_k}\leq\bar{f}^{i}_{S_n},\ \sum_{t\in T}f^{p}_{M_k D_t}\leq\bar{f}^{p}_{M_k},\ f^{p}_{D_t}\leq\bar{f}^{p}_{D_t},\ \sum_{k\in K}f^{i}_{e_n M_k}\leq\bar{f}^{i}_{e_n},\ f^{p}_{u_k D_t}\leq\bar{f}^{p}_{u_k},\ \sum_{t\in T}f^{p}_{eD_t}\leq\bar{f}^{p}_{eD_t}$$
$$\sum_{n\in N}\sum_{k\in K}\left(f^{i}_{S_n M_k}+f^{i}_{e_n M_k}\right)\geq\sum_{k\in K}\sum_{t\in T}\alpha_i\lambda_{ip}f^{p}_{M_k D_t},\ \sum_{k\in K}\sum_{t\in T}\left(f^{p}_{M_k D_t}+f^{p}_{u_k D_t}\right)+\sum_{t\in T}f^{p}_{eD_t}\geq\sum_{t\in T}\alpha_p f^{p}_{D_t}$$
$$\sum_{n\in N}\sum_{k\in K}\sum_{i\in I}C_{S_n M_k}f^{i}_{S_n M_k}+\sum_{k\in K}\sum_{t\in T}\sum_{p\in P}C_{M_k D_t}f^{p}_{M_k D_t}+\sum_{t\in T}\sum_{p\in P}C_{D_t}f^{p}_{D_t}$$
$$+\sum_{n\in N}\sum_{k\in K}\sum_{i\in I}h^{i}_{e_n M_k}f^{i}_{e_n M_k}C_{e_n M_k}+\sum_{k\in K}\sum_{t\in T}\sum_{p\in P}f^{p}_{u_k D_t}C^{p}_{u_k D_t}+\sum_{t\in T}\sum_{p\in P}h^{p}_{eD_t}f^{p}_{eD_t}C^{p}_{eD_t}\leq\bar{C}$$
$$R_s\geq\bar{R}$$
$$\Delta d=d^{p}-\sum_{t\in T}f^{p}_{D_t} \tag{3.23}$$

4 Case study-relief tents supply in the Ya'an earthquake

4.1 Case description

On 20 April 2013, an earthquake measuring 7.0 on the Richter scale hit Lushan County of Ya'an City. This article takes the relief tents supply as a case study, analyzes the Ya'an earthquake relief tents supply chain, and establishes a reliability optimization model.

For the supply of relief tents, in Sichuan Province, the Department of Civil Affairs of Sichuan Province transferred relief tents reserves, and large manufacturers of relief tents in Sichuan province (such as Chengdu Company F) organized emergency production. Nationwide, the Ministry of Civil Affairs transferred 8 million relief tents to Sichuan Province from nine central relief supply reserves of Hefei, Zhengzhou, Wuhan, Changsha, Chengdu, Nanning, Kunming, Xi'an and Lanzhou. In addition, there are relief supplies sent from tents manufacturers in other provinces. Taking a province as a unit, the tents supplied by the manufacturing enterprises from other provinces were: Shandong S company sent 500 tents and Zhejiang Z Company 1200 tents.

For the relief demand, the hard-hit areas are Lushan County, Baoxing County and Tianquan County, according to incomplete statistics, the number of affected people of the three counties are 14 million, 5.8 million and 11.7 million, respectively. If each tent can accommodate 3 ~ 4 persons, the three affected counties would need 40 thousand, 17 thousand and 33 thousand relief tents, respectively, which is a total of 90 thousand tents.

Through the analysis of tent supply chain, this article obtains the supply chain construction of tents demand. For the supply of raw supplies, after every tent manufacturer establishes their own raw supplies buffer inventory, it needs supplies, such as constitute tent fabrics, the bottom of tent fabrics and jackstay; for relief supplies, three companies from F company (Chengdu and Sichuan), S company (Shandong) and Z company (Zhejiang) are responsible for the production and supply, and they may organize additional production to ensure the mobilization task. In addition, nine central relief supply reserves of Hefei, Zhengzhou, Wuhan, Changsha, Chengdu, Nanning, Kunming, Xi'an and Lanzhou also participate in this task. For the relief demand, the total forecasted number of tents demanded is 90 thousand. There are three disaster demand points, which are located in Lushan County, Baoxing county and Tianquan county.

4.2 Creation of the optimization model

4.2.1 Case study

According to the above description, this model can obtain the supply chain structure of relief tents, as shown in Fig. 1. There are nine raw material suppliers S_1, S_4 and S_7 supply raw supplies i_1, which is tent fabrics. S_2, S_5 and S_8 supply the raw supply i_2, which is the bottom of the tent fabrics; S_3,S_6 and S_9 supply raw supplies i3,which are jackstays; M_1,M_2 and M_3 are three tents manufacturers, and they are from Sichuan, Shandong and Zhejiang; there are nine central relief supply reserves,which are $e_1 \sim e_9$, and it is assumed that there are no differences in the tents supplied; D_1, D_2 and D_3 are the three demand centers, and they are responsible for receiving relief tents and allocating the tents to Lushan County, Baoxing County and Tianquan County. The supply relationship is shown in Fig. 2.

From Fig. 2, the basic block diagram of the reliability of the supply chain system can be obtained, as shown in Fig. 3. Based on the reliability of the basic block diagram, the reliability of the supply chain can be given by (4.1). Among them, when $k = 1$, $n = 1,2,3$; and when $k = 2$, $n = 4,5,6$; when $k = 3$, $n = 7,8,9$. w_{D_t} represents the proportion of the forecasted demand of each demand point in the total demand.

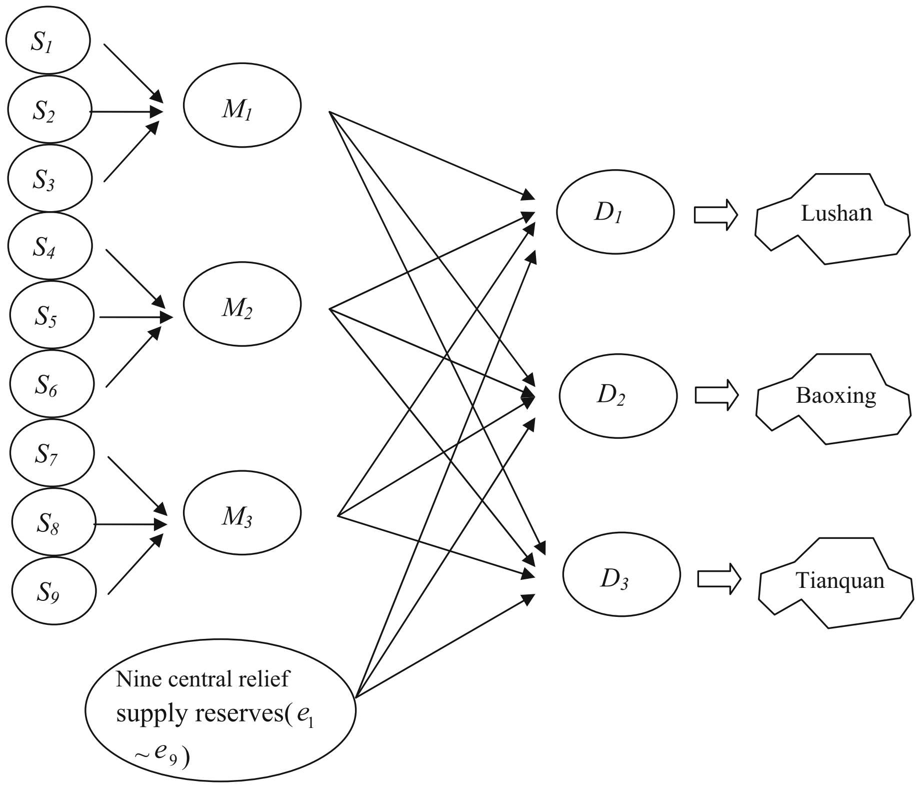

Fig. 2 Supply chain structure of the relief tents

$$
\begin{aligned}
R_s &= \sum_{t=1}^{3} w_{D_t} R_{SMD_t} \\
R_{SMD_t} &= 1 - \prod_{\substack{k=1,2,3\\ t=1,2,3}} (1 - R_{SM_kD_t}) \cdot \prod_{\substack{j=1,2,\ldots,9\\ t=1,2,3}} (1 - R_{e_jD_t}) \\
R_{SM_kD_t} &= [1 - (1 - R_{M_kD_t})(1 - R_{u_kD_t})] \cdot \prod_{\substack{n\in[1,9]\\ k=1,2,3\\ t=1,2,3}} [1 - (1 - R_{S_nM_k})(1 - R_{e_{S_n}M_k})]
\end{aligned}
\tag{4.1}
$$

4.2.2 Parameter determination

The parameters of the relief tent supply chain reliability optimization model are shown in Tables 3 and 4. In Table 3: first, the number of product BOMs is calculated by the quantity demanded of the fabric and the bottom material in a single relief tent, and the jackstay of a tent is divided into horizontal and vertical portions. Accordingly, the corresponding parameter value is 2. Second, the upper limit value of the material distribution capacity of each demand center is 1.1 times the forecast demand. In Table 4: first, the values of parameters *a* and *b* determine the operating cost. These values need to be increased when

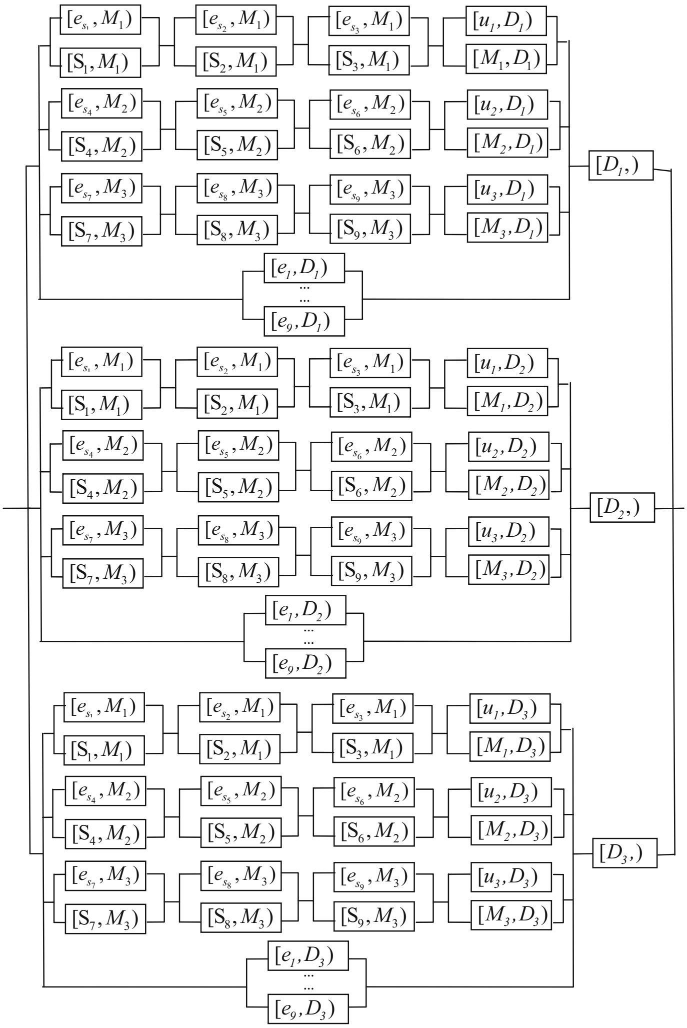

Fig. 3 The basic unit reliability block diagram of the relief tent supply chain

improving the unit reliability of its supply chain. The greater that a and b are, the higher the operating costs are. Therefore, the increase of the transport cost is a crucial factor. In accordance with the distance to Ya'an city from near to far, the central relief supply reserves and the manufacturers are arranged as follows: Chengdu (180 km), Kunming (785 km), Xi'an (859 km), Lanzhou (1056 km), Wuhan (1282 km), Changsha (1334 km), Zhengzhou (1335 km), Nanning (1377 km), Hefei (1557 km), Shandong S company (1751 km) and Zhejiang Z company (1998 km). According to this following sequence, the corresponding values parameters a and b are obtained; Second, because the differences in the distance from the individual reserve storages to Ya'an city are small, such as Zhengzhou and Nanning, this article sets the same parameter values of these two units. Third, this article assumes that the parameters a and b are the same from the same reserve storage to the three demand points. For example, the parameter of $[M_1,D_1)$ is equal to the parameter of $[M_1,D_2)$, and it is equal to the parameter of $[M_1,D_3)$.

Table 3 Some parameters of relief tents supply chain reliability optimization model

Parameter type	The subject belongs to	Parameter symbols	Value
Product BOM	Relief tents (*P*)	$\lambda_{i_1 p}$	1
		$\lambda_{i_2 p}$	1
		$\lambda_{i_3 p}$	2
Productive capacity of enterprise	Supplier	S_1	1400
		S_2	1300
		S_3	3000
		S_4	1300
		S_5	1500
		S_6	2800
		S_7	2000
		S_8	1800
		S_9	3700
	Manufacturer	M_1	1500
		M_2	1500
		M_3	2000
Distribution capability of the disaster point	Disaster point	D_1	40,000
		D_2	17,000
		D_3	33,000

Table 4 The values of a_{ij} and b_{ij} of the relief tent supply chain reliability optimization model

Logistics	Elementary unit	a_{ij}	b_{ij}
i_1	$[S_1, M_1)$	3	5
	$[S_4, M_2)$	2	6
	$[S_7, M_3)$	3	4
i_2	$[S_2, M_1)$	3	4
	$[S_5, M_2)$	3	5
	$[S_8, M_3)$	5	6
i_3	$[S_3, M_1)$	4	5
	$[S_6, M_2)$	4	4
	$[S_9, M_3)$	6	3
P	$[M_1, D_1)$	3	4
	$[M_2, D_1)$	13	13
	$[M_3, D_1)$	13	14
	$[e_1, D_1)$	3	4
	$[e_2, D_1)$	6	7
	$[e_3, D_1)$	8	7
	$[e_4, D_1)$	8	9
	$[e_5, D_1)$	10	10
	$[e_6, D_1)$	12	11
	$[e_7, D_1)$	12	11
	$[e_8, D_1)$	13	11
	$[e_9, D_1)$	13	12

For the emergency mobilization strategies, this article assumes that the buffer inventory of all raw material suppliers is equal to 0.2 times the upper limit of its production capacity; the number of relief tents produced through the additional production strategy by each manufacturing company is 0.2 times the maximum formal production capacity, and each of the nine central relief supply reserves has 10,000 rescue tents. For the operating cost, this model assumes that the inventory cost of buffer stock set by the raw material suppliers is 0.8, which is expressed as h_s, the cost increase coefficient is 1.3, when manufacturing enterprises organize the additional production of relief tents; and the tent inventory cost of the central relief supply reserves is 8.

Finally, this article assumes that the demand expansion coefficient of the bullwhip effect in every link of the tent supply is 1.05, the reliability of each unit is higher than 0.5; and the reliability for each demand center is 1.

4.2.3 Creation of model

It is easy to create the supply chain reliability optimization model of relief tents, as shown in the following equations. Among the equations, formula (4.2) represents the production capacity constraint, formula (4.3) represents the supply balance constraint that considers the bullwhip effect, formula (4.4) represents the supply chain operating cost constraint, and formula (4.5) represents the reliability constraint of the entire supply chain.

$$Min \Delta d$$

$$s.t.\ \sum_{i=1}^{3}\sum_{n=1}^{9}\sum_{k=1}^{3} f^{i}_{S_n M_k} \le \bar{f}^{i}_{S_n}, \sum_{k=1}^{3}\sum_{t=1}^{3} f^{p}_{M_k D_t} \le \tilde{f}^{p}_{M_k}, \sum_{t=1}^{3} f^{p}_{D_t} \le \bar{f}^{p}_{D_t},$$

$$\sum_{i=1}^{3}\sum_{n=1}^{9}\sum_{k=1}^{3} f^{i}_{e_{S_n} M_k} \le \bar{f}^{i}_{e_n}, \sum_{t=1}^{3} f^{p}_{u_k D_t} \le \bar{f}^{p}_{u_k}, \sum_{j=1}^{9}\sum_{t=1}^{3} f^{p}_{e_j D_t} \le \bar{f}^{p}_{e_j D_t}; \tag{4.2}$$

$$\sum_{i=1}^{3}\sum_{n=1}^{9}\sum_{k=1}^{3} (f^{i}_{S_n M_k} + f^{i}_{e_{S_n} M_k}) \ge \sum_{i=1}^{3}\sum_{n=1}^{9}\sum_{k=1}^{3} 1.05 \times \lambda_{ip} f^{p}_{M_k D_t},$$

$$\sum_{k=1}^{3}\sum_{t=1}^{3} (f^{p}_{M_k D_t} + f^{p}_{u_k D_t}) + \sum_{j=1}^{9}\sum_{t=1}^{3} f^{p}_{e_j D_t} \ge \sum_{t=1}^{3} (1.05 \times f^{p}_{D_t}) \tag{4.3}$$

$$\sum_{n=1}^{9}\sum_{k=1}^{3}\sum_{i=1}^{3} C_{S_n M_k} f^{i}_{S_n M_k} + \sum_{k=1}^{3}\sum_{t=1}^{3} C_{M_k D_t} f^{p}_{M_k D_t} + \sum_{t=1}^{3} f^{p}_{D_t} + \sum_{n=1}^{9}\sum_{k=1}^{3}\sum_{i=1}^{3} h^{i}_{e_{S_n} M_k} f^{i}_{e_{S_n} M_k} C_{e_{S_n} M_k}$$

$$+ \sum_{k=1}^{3}\sum_{t=1}^{3} f^{p}_{u_k D_t} C^{p}_{u_k D_t} + \sum_{j=1}^{9}\sum_{t=1}^{3} h^{p}_{e_j D_t} f^{p}_{e_j D_t} C^{p}_{e_j D_t} \le \bar{C} \tag{4.4}$$

$$R_s \ge \bar{R} \tag{4.5}$$

$$\Delta d = d^p - \sum_{t=1}^{3} f^{p}_{D_t}$$

$$0.5 < R_s < 1$$

4.3 Model calculation and analysis

This article calculates the nonlinear programming model with the LINGO software. The model assumes that the budget is 10 million yuan, and that the minimum reliability limit is 0.9. The optimization results are shown in Table 5. The optimal solution of the function is 2677, which means that there are 2677 tents that are not supplied in a timely manner. Table 5 shows the optimal reliability and the flow for each basic unit in this supply chain system, and it obtains that $f_{e_1D} \sim f_{e_9D}$ are 10,000, 10,000, 10,000, 10,000, 10,000, 10,000, 10,000, 10,000, 6409, and the sum is 86,409, and the proportion of total demand is 96%. Thus, the roles of the relief reserve and the reliability are critical for the supply capability of entire supply chain. This article performs the further analysis.

4.3.1 Analysis of influencing factor for the disaster relief supply

Based on the optimization model, this article performs a detailed quantitative analysis of the two factors, the budget and the reliability.

Through the adjustment of the budget, the model can obtain the relationship between supply shortage of relief tents and budget, as shown in Table 6 and Fig. 4. When the budget is 10.6 million yuan, relief tents supply shortage is 4930. With the increase in the budget, supply shortages of relief tents show a decreasing trend, and the rate of decrease decelerates. When the budget reaches 115 million yuan, supply shortage of relief tents is 0, obviously, this is the perfect state of relief material supply. When budget continues to increase, the supply shortage of relief tents remains unchanged, since the reason is related to the upper limit of supply capacity that is initially set in this case. When the budget exceeds a certain value (in this case, the certain value is 11.5 million yuan), there is no supply shortage, even if the shortage is negative. Therefore, two conclusions can be obtained: (1) increasing the budget can improve the effect of relief supply mobilization, and a higher budget results in the lower marginal efficiency; and (2) when the state plans the mobilization budget, it should perform the predictive analysis scientifically.

Theoretically, by adjusting the minimum of the reliability of relief tents supply, one can obtain the relationship between the supply shortage of relief tents and the reliability. Through the application of the model, the following is found. When the budget is 10 million yuan, and the minimum reliability of the supply chain is 0.9, the model obtains the optimal solution. The supply shortage reaches its minimum, which is 2677, and the total reliability of supply chain has been up to 0.99947. This phenomenon may be caused by two reasons. The first reason is that the emergency mobilization budget is too high, and the second reason involved the supply chain structure. Thus, this article gradually decreases the budget, and it discovers that the optimal total reliability does not change significantly. The reason for this result is the parallel structure of the supply chain. Through analyzing Table 5, it is found that even though the total reliability is 0.999, most of the basic unit reliabilities are 0.5, which is the minimum unit reliability that is set initially. In particular, among the supply chain, two basic units that have the largest flow, which are $[e_1, D_2)$ and $[e_9, D_1)$, have the optimal unit reliability of 0.5 too.

Based on the above analysis, the following conclusions can be drawn. During the development of reliability, it's meaningless to maximize the unit reliability by spending larger costs. The structure of the supply chain plays a more crucial role. Therefore, it is more helpful to analyze the current situation of the humanitarian relief supply in our country and to plan the supply chain's structure scientifically to guarantee the total reliability of the humanitarian relief supply chain.

Table 5 The optimization results of the model When $C = 10{,}000{,}000$ and $\overline{R} = 0.9$

	$[D_1,)$	$[D_2,)$	$[D_3,)$	$[S_1,M_1)$	$[S_2, M_1)$	$[S_3,M_1)$	$[S_4,M_2)$	$[S_5,M_2)$
Reliability	1	1	1	0.5	0.5	0.5	0.5	0.5
Flow	40,000	14,323	33,000	1280	1300	2520	1300	1260
	$[S_6,M_2)$	$[S_7,M_3)$	$[S_8,M_3)$	$[S_9,M_3)$	$[M_1,D_1)$	$[M_1,D_2)$	$[M_1,D_3)$	$[M_2,D_1)$
Reliability	0.5	0.5	0.5	0.5	0.528	0.529	0.5	0.5
Flow	2560	1760	1800	3580	0	0	1486	1486
	$[M_2,D_2)$	$[M_2,D_3)$	$[M_3,D_1)$	$[M_3,D_2)$	$[M_3,D_3)$	$[e_{s1},M_1)$	$[e_{S2},M_1)$	$[e_{S3},M_1)$
Reliability	0.994	0.907	0.5	0.994	0.5	0.5	0.5	0.5
Flow	0	0	1505	0	495	280	260	600
	$[e_{s4},M_2)$	$[e_{S5},M_2)$	$[e_{S6},M_2)$	$[e_{s7},M_3)$	$[e_{S8},M_3)$	$[e_{S9},M_3)$	$[u_1,D_1)$	$[u_1,D_2)$
Reliability	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.999
Flow	260	300	560	400	360	740	74	0
	$[u_1,D_3)$	$[u_2,D_1)$	$[u_2,D_2)$	$[u_2,D_3)$	$[u_3,D_1)$	$[u_3,D_2)$	$[u_3,D_3)$	$[e_1,D_1)$
Reliability	0.5	0.5	0.907	0.5	0.5	0.897	0.5	0.5
Flow	0	0	0	74	101	0	59	2545
	$[e_1,D_2)$	$[e_1,D_3)$	$[e_2,D_1)$	$[e_2,D_2)$	$[e_2,D_3)$	$[e_3,D_1)$	$[e_3,D_2)$	$[e_3,D_3)$
Reliability	0.5	0.525	0.5	0.5	0.5	0.5	0.5	0.5
Flow	7455	0	508	2495	6997	3286	870	5844
	$[e_4,D_1)$	$[e_4,D_2)$	$[e_4,D_3)$	$[e_5,D_1)$	$[e_5,D_2)$	$[e_5,D_3)$	$[e_6,D_1)$	$[e_6,D_2)$
Reliability	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Flow	5422	796	3782	4514	991	4495	5374	818
	$[e_6,D_3)$	$[e_7,D_1)$	$[e_7,D_2)$	$[e_7,D_3)$	$[e_8,D_1)$	$[e_8,D_2)$	$[e_8,D_3)$	$[e_9,D_1)$
Reliability	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Flow	3807	5374	818	3807	5421	796	3783	6388
	$[e_9,D_2)$	$[e_9,D_3)$						
Reliability	0.525	0.5						
Flow	0	21						

Table 6 The relationship between supply shortage of relief tents and budget

C	1060	1070	1080	1090	1100	1110	1120	1130	1140	1150	1160
Δd	4930	4367	3803	3230	2677	2113	1550	986	423	0	0

The unit of budget C is million yuan

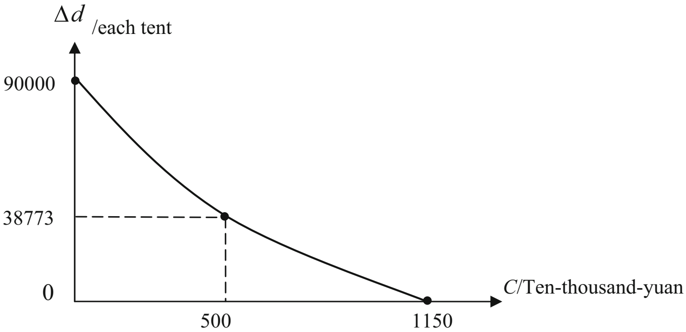

Fig. 4 The relationship between supply shortage of relief tents and budget

Table 7 The comparison of the effects among different emergency mobilization strategies

Different emergency mobilization strategies	Δd
Doesn't use raw material buffer inventory strategy	3306
Doesn't use additional production strategy	2917
Doesn't use relief supply reserve strategy	84,971

4.3.2 The comparison of the effects among different emergency mobilization strategies

In this case, the comparison of the effects can be achieved by adjusting the parameters of the initial setting. In ensuring the invariability of the mobilization budget ($C = 1000$ million yuan) and the minimum reliability ($R = 0.9$), the model adopts the three following settings: (1) the value of raw supplies buffer inventory is set at 0, (2) the yield of the additional production is set at 0, and (3) the inventory of relief supply reserve is set at 0. We observe the changes in the effects after optimizing the humanitarian relief supply, as shown in Table 7.

Table 7 shows that when the three emergency mobilization strategies are not used, the supply shortages are 3306, 2917 and 84,971 respectively, the total reliabilities are 0.997, 0.999 and 0.900 respectively. Therefore, relief supply reserve strategy plays a more crucial role. When decision makers give up setting the relief supply reserve, the supply shortage increases to 94% (84,971/90,000), the reliability of the supply chain after optimization approaches to the minimum reliability constraint, and the effect of supply is poor. Thus, during the development of the structural planning and reliability of humanitarian relief supply chain, decision makers should vigorously strengthen investments in relief supply reserves.

4.4 Managerial and practical implications

Several interesting managerial and practical implications emerge from the above analysis. First, increasing the investment of emergency mobilization cost (budget) will improve the effectiveness of humanitarian relief supply, and the emergency mobilization cost (budget) has a positive correlation with the effectiveness of humanitarian relief supply. However, with the increase of emergency mobilization cost (or budget), the marginal utility of humanitarian relief supply diminishes. Therefore, it is recommended that the emergency management department should increase the supply of relief supplies. Meanwhile, they must also scientifically plan the budget boundary value of emergency mobilization cost and try their best to avoid the phenomena of waste of resources, uneconomical investment, and excessive mobilization.

Second, design the structure of the humanitarian relief supply chain rationally and configure the reliability of each component scientifically. The optimization results show that under the condition of a reasonable system structure, improving the emergency mobilization cost (or budget) has no obvious effect on the total reliability improvement of the humanitarian relief supply chain. The total reliability of the supply chain can reach a large value (e.g., 0.99) through properly combination even though the reliabilities of most of the supply chain components are low (e.g., 0.5). Consequently, persons responsible for constructing humanitarian relief supply chain reliability should rationally plan the supply chain composition structure rather than maximize the reliability of each component.

Third, increase the investment of national-level relief supplies reserve. By adjusting relevant parameters, this article observes that in each of the parameters, the strategy of relief supplies reserve has a more significant effect on relief supply than the other two strategies. Therefore, the decision-makers responsible are suggested to utilize the strategies in the following order: First using relief supplies reserve, then using raw material buffer inventory, and additional production. This is important as it provides guidance in terms of the order of utilizing various emergency mobilization strategies.

5 Conclusion and future research

The humanitarian relief supply chain is an emergent area that demands tools to support decisions that are made under adverse conditions. Although some studies provide insight into various disaster operations efforts, the optimization of models for reliability of humanitarian relief that consider several objectives has not been addressed in the literature until recently. This article presents the SCRIOM based on three emergency mobilization strategies, and the model provides a means for optimizing the reliability of a humanitarian relief supply chain in a quantitate way. The analysis demonstrates that increasing mobilization investment is helpful to the improve the supply effectiveness. However excessive investment can not significantly improve the total reliability of the humanitarian relief supply chain and blindly pursuing the maximization of unit reliability is not economical. Importantly, the structure of the supply chain plays an important role in total reliability. Even though the model is specifically designed for the humanitarian relief supply chain, it could be extended to commercial supply chain under adverse conditions. The model has been applied to a case study based on the 2013 Ya’an earthquake to illustrate its behavior with promising results.

In the future, more considerations could be conducted to improve the research. One is to apply the presented SCRIOM into other relief supplies supply problems considering more practical constraints. Another is to consider the multiple relief supplies humanitarian supply chain with different structures to find the most reliable supply chain configuration mode.

Acknowledgements This work was supported by the National Natural Science Foundation of China under Grant 71473015.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interests.

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