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Optimizing Pre-Disaster Reserve Planning Through Multi-Stakeholder Collaboration Using Genetic Algorithm

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Abstract. The occurrence of earthquake has become increasingly abrupt, leading to significant economic losses. Pre-disaster planning has always been an effective measure to ensure the quality of relief chain and reduce costs. In this regard, cooperative governance has been adopted by various countries, but its implementation has not been ideal. Therefore, this study incorporates stakeholders into a reserve network, integrating each stakeholder's willingness to cooperate into the model to derive an effective reserve solution. To align with reality, a set of scenario datasets is first generated to depict the transportation feasibility of each warehouse. Then, this study employs NSGA-II to solve the model. The results are evaluated through a set of Pareto solutions. Experimental findings indicate that the proposed model can significantly reduce the imbalance of interests between the stakeholders, thereby achieving a win-win cooperation outcome.

Keywords: Earthquake, supply chain, cooperative governance

1. Introduction

Earthquakes are among the most perilous natural disasters. According to the 2023 Global Natural Disaster Assessment Report, earthquakes claimed 62,451 lives, a number significantly above the historical average. In 2024, earthquakes in China resulted in an economic loss of 3.79 billion yuan. Numerous countries have explored various collaborative strategies for resource reserves to mitigate the risk of supply chain disruptions while optimizing costs. The "Sendai Framework for Disaster Risk Reduction 2015-2030" advocates for the adoption of cooperative governance, which has been further reinforced through laws and regulations. The national emergency response system released by Canada in 2005 supports cooperation between various public and private sectors. The United States emphasizes the coordination of materials between governments in FEMA's strategic planning. China's "National Emergency Management System Plan during the 14th Five-Year Plan Period" [1] emphasizes the need to facilitate supply flow between regions, achieving a more agile relief.

Despite significant progress in relief efforts compared to the past, the issue of balancing supply preparedness still persists. During the initial rescue phase, some areas continue to face significant shortages, as exemplified by the 7.8 magnitude earthquake in Turkey in 2023. Conversely, some regions face waste due to expired supplies, such as the expired bottled water in Newark in 2019 and expired food in Jixian County, Shanxi in 2023. An effective solution is cooperative governance, but its current implementation has not been satisfactory. The "Henan Zhengzhou '7·20' Heavy Rain Disaster Investigation Report" [2] pointed out weak cooperation mobilization capabilities and insufficient information sharing. In the case of Hurricane Katrina, cooperative actions were initiated five days after the disaster.

To address this problem, this paper fully implements the concept of collaborative governance, where the relief chain involves multiple humanitarian organizations and manufacturers. Adhering to the principle of equal cooperation, the interests of each organization are taken into account to maintain the healthy development. The structure of this paper is as follows: Section 2 reviewes previous work. Section 3 outlines a series of indicators. Section 4 designs a bi-objective nonlinear model, and presents the solution approach. Section 5 conducts numerical experiments to test the model. Section 6 presents the conclusions.

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2. Related Works

Previous literature, based on systems management theory, points out that fairness and trust are key factors for the smooth cooperation. It is necessary to clearly define the interests and responsibilities of each stakeholder involved. Schulz and Blecken [3] pointed out the lack of transparency in existing interests as an obstacle to cooperation through case analysis. Toyasaki et al. [4] pointed out from an inventory management perspective that organizational behavior may not align with prior expectations, and there is a need to evaluate the motivations. Roh et al. [5] provided a solution for warehouse location under international aid and highlighted the importance of cooperation. Balcik et al. [6] determined the investment behavior of each stakeholder in government cooperation based on insurance to allocate costs. Guzmán-Cortés et al. [7] evaluated the impact of shared resources, infrastructure, and other factors on collaborative rescue time, and provided optimal policy recommendations. Guerrero et al. [8] conducted a comprehensive analysis of two acute disaster relief cases, highlighting cooperation challenges such as goal alignment, understanding, and commitment.

An increasing number of studies have addressed the reserve from the perspective of operations optimization. Li and Liu [9] used distributionally robust optimization to solve a collaborative network, taking into account the development levels of different countries in cost allocation. Modarresi and Maleki [10] addressed warehouse location and reserve issues in public-private partnerships, using flexible contracts in terms of quantity to meet relief needs. Kord and Samouei [11] also used flexible quantity contracts but constructed more complex scenarios, including demand uncertainty and a four-level supply chain. Li et al. [12] expanded the scope of resource reserves during the preparation phase, incorporating capacity reservations and backup resources into consideration. Huang et al. [13] proposed reserve recommendations for inventory, capacity, and market capital under different scenarios, focusing on cost and resource utilization efficiency.

Currently, collaborative governance involving multiple stakeholders still requires further exploration, including considerations of stakeholders' interests, a comprehensive exploration of the disaster relief cycle, and the uncertainties in transportation. In this paper, a bi-level multi-objective model considering pre-disaster reserves and post-disaster transportation is proposed to maximize system benefits. Specifically, to enhance the practical applicability, a set of scenario datasets is generated to simulate the transportation feasibility, and a learning curve is introduced to model the emergency procurement process.

3. Problem Description

The main stakeholders involved include the humanitarian organization (HO) H and the manufacturer (MFR) M, with the former acting as the decision-maker. Before the disaster, the HOs and the MFRs establish a cooperation agreement, stipulating that part of the supplies will be stored in the organization's warehouse, while the other part will be stored by the manufacturer. After the disaster occurs, the local organization can request the release of all supplies within the region, but there is a possibility of transportation failure at the warehouse. If there is unmet demand, emergency procurement will be carried out. If the disaster does not occur, owners will handle the remaining supplies independently. The decision-making process is shown in figure 1:

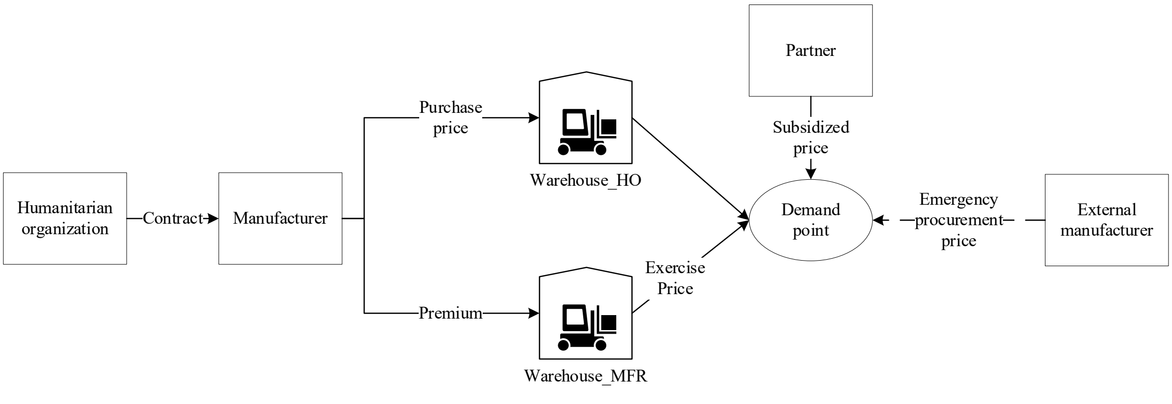

Fig. 1: Disaster relief reserve planning concept diagram

To ensure the solvability and realism, the following assumptions are made:

- The quality of supplies is not considered within the validity period.
- The transportation, production, and assistance costs incurred during relief are borne by the local HO.
- The disaster is primarily caused by a shallow earthquake, occurring at only one affected point.
- The manufacturer adheres to the commitment and stocks sufficient supplies.

The emergency procurement process after the disaster is the result of communication between the organization and multiple suppliers. Therefore, with the changes in demand, the procurement time changes non-linearly. This paper introduces the learning curve to simulate this process, as shown in Formula 1. The minimum number of supplies that a manufacturer can deliver is considered as one procurement unit, where x represents the number of units, a represents the market response time required to procure one unit, and b represents the learning index, with a value range of $[0,1]$.

$$G(x) = ax^b \tag{1}$$

4. Mathematical Model and Solution

The goal is to construct a model with the maximum cooperative benefits. Therefore, the average time and cost for each stakeholder in an independent state are first labeled as AC_h and AT_h. Then the objectives in a cooperative state are obtained, as indicated by formula 2 and formula 3.

$$F_a(h) = \sum_{i \in I^h} \sigma_i \left\{ \sum_{s \epsilon S} \left[\left(\prod_{j \in J} {\tau_{ij}}^{s_j} (1 - \tau_{ij})^{1-s_j} \right) \cdot \left(\sum_{j \in J} s_j TN_{ij}^s t_{ij} + G(EN_i^s) \right) \right] \right\} \tag{2}$$

$$\begin{aligned} F_b(h) = &\sum_{i \in I^h} \sigma_i \sum_{s \in S} \left(\prod_{j \in J} {\tau_{ij}}^{s_j} (1 - \tau_{ij})^{1-s_j} \right) \cdot \left\{ \sum_{j \in J} s_j \left[TQ_{ij}^s cg + TN_{ij}^s (cf + t_{ij} ct) \right] + ep_h EQ_i^s \right\} \\ &+ \sum_{i \in I} \sigma_i \sum_{s \in S} \left(\prod_{j \in J} {\tau_{ij}}^{s_j} (1 - \tau_{ij})^{1-s_j} \right) \left(\sum_{j \in M^n} s_j TQ_{ij}^s oc_h \right) + W_h [rc_h - v_h (1 - \theta_h)] + rp_h W_m \end{aligned} \tag{3}$$

where I represents the set of affected points, J represents the set of warehouses, S denotes the set of transportation scenarios for all warehouses, $s_j \epsilon \{0,1\}$ indicates whether transportation is possible, σ_i represents the disaster probability at potential point i, τ_{ij} is the feasibility factor of aid, TN_{ij}^s refers to the number of transportation trips, t_{ij} represents the transportation time, EN_i^s refers to the number of units purchased for emergency procurement, TQ_{ij}^s represents the quantity transported, cg represents the loading cost required for each unit of supply, cf represents the fixed cost for each transportation, ct represents the transportation cost per time, ep_h represents the emergency price, EQ_i^s represents the emergency quantity, oc_h represents the execution price, W_j representes the warehouse stock quantity, rc_h represents the procurement price before the disaster, v_h represents the remaining value, θ_h represents the overall probability of the area, rp_h representes the premium; d_i represents the demand.

The calculation formula for the subsidy benefit is $PI_h = pm_h \sum_{s \epsilon S} \sum_{i \in I - I^h} \sigma_i \left(\prod_{j \in J} {\tau_{ij}}^{s_j} (1 - \tau_{ij})^{1-s_j} \right) \sum_{j \in J^n} TQ_{ij}^s$, and the subsidy cost paid is $PO_h = \sum_{s \in S} \sum_{i \in I^h} \sigma_i \left(\prod_{j \in J} {\tau_{ij}}^{s_j} (1 - \tau_{ij})^{1-s_j} \right) \sum_{k \epsilon H - h} \sum_{j \in J^k} pm_k TQ_{kj}^s$. The constructed upper-level model is as follows:

$$min\, F_c = \left(\sum_{h \in H} \frac{F_a(h)}{AT_h}, \sum_{h \in H} \frac{F_b(h) - PI_h + PO_h}{AC_h} \right) \tag{4}$$

$$\boldsymbol{s.t.} \sum_{s \in S} \left[\left(\prod_{j \in J} {\tau_{ij}}^{s_j} (1 - \tau_{ij})^{1-s_j} \right) \cdot \left(\sum_{j \in J} s_j TN_{ij}^s t_{ij} + G(EN_i^s) \right) \right] \le T, \forall i \in I \tag{5}$$

$$W_h \le max(d_1, d_2, \dots, d_{I^h}), \forall h \in H \tag{6}$$

$$W_m \le max(d_1, d_2, \dots, d_{I^h}), if\ m \epsilon M^h, \forall h \in H \tag{7}$$

$$EQ_i^s = max\left(d_i - \sum_{j\in J} s_j W_j, 0\right), \forall i \in I \tag{8}$$

$$W_j, EQ_i^s, TQ_{ij}^s \in \mathbb{N}, \forall i \in I, s \in S, j \in J \tag{9}$$

The lower-level model is as follows:

$$max\ F_d = \sum_{j\in J} \frac{s_j TQ_{ij}^s}{TN_{ij}^s t_{ij}} \tag{10}$$

$$\boldsymbol{s.t.} TQ_{ij}^s = 0, if\ s_j = 0, \forall j \in J, s \in S, i \in I \tag{11}$$

$$TQ_{ij}^s - W_j s_j = 0, if \sum\nolimits_{j\in J} W_j s_j \le d_i, \forall j \in J, s \in S, i \in I \tag{12}$$

Constraint 5 ensures that the expected rescue time does not exceed the expected value in all scenarios. Constraints 6 and 7 ensure that the reserve quantity does not exceed the maximum demand. Constraints 8 and 12 ensure that emergency procurement is only initiated when the current available supplies do not meet the demand. Constraint 11 ensures that the scenario logic constraints hold.

In solving the lower-level model, this paper aims to reduce the overall perception of suffering by improving the speed. With the idea of optimizing each transportation, first calculate the maximum quantity that needs to be transported by using the formula $d' = min(d, L)$, where d is the initial demand and L is the maximum loading capacity. Then using the formula d'/t_{ij} to calculate the transportation speed for each warehouse. Select the warehouse with the highest speed as the main transportation hub. Finally continuously update the demand and repeat the process until it reaches zero. For the bi-objective hybrid model proposed, the non-dominated sorting genetic algorithm (NSGA-II) is a classical solution method. Solutions are selected based on the Manhattan distance and binary tournament algorithm to maintain the diversity of the solutions. In calculating the fitness of individuals, obtaining τ_{ij} is a significant challenge in practice. Therefore, this paper uses the scenario dataset to simulate, with the individual fitness is the expected value.

5. Numerical Experiments and Results

5.1. Parameter Settings

The paper constructs cooperation scenarios for three regions, with a total of six potential demand points. The basic parameters are shown in Table 1.Set $rc = [120,140,130]$. Set rp, oc, op, v, and p to 80%, 50%, 200%, 20%, and 85% of rc, respectively. The transportation feasibility factors are sampled based on Beta distribution [14]. Set a = 10, b = 0.5, the allowable maximum rescue time $T = 48$. Remaining values refer to the data in references [15].

Table 1: Basic parameters table

		HO#1		HO#2	HO#3		
		Point1	Point2	Point3	Point4	Point5	Point6
σ_i		0.12	0.18	0.1	0.22	0.12	0.28
d_i		3496	6516	7200	3498	6023	9677
t_{ij} (Shipping origin)	Warehouse_HO#1	5.4	5.8	7.64	11.77	13.39	14.45
	Warehouse_HO#2	8.23	8.01	6.94	12.64	14.26	15.32
	Warehouse_HO#3	11.27	12.16	11.64	6.75	8.92	8.16
	Warehouse_MFR#1	6.26	7.15	8.06	11.22	12.83	13.9
	Warehouse_MFR#2	7.62	7.45	5.63	11.16	12.78	13.84
	Warehouse_MFR#3	8.25	9.14	8.62	8.67	10.28	11.34

5.2. Calculation Result

First, solve for the time and cost values in the non-cooperative scenario by setting s_j. The results are as follows for each region: AC = 793647.05, 419526.96, 1652800.91; AT = 5.56, 2.67, 12.51. Both data are influenced by the disaster probability, which aligns with the reality that more attention needs to be given to important areas under system planning. After obtaining a set of Pareto solutions, reducing them to a specific solution is an effective way to visually inspect the values. This paper uses the balanced programming method, with the weights wt of the two objectives and the corresponding solution values shown in Table 2. It can be seen that HO#2, with the lowest disaster probability and highest price, tends to rely on contracted manufacturers for storage or assistance from partners and external procurement, with a weak willingness to maintain its own reserves. HO#3, when $wt = [0.2, 0.8]$, also maintains a moderate level of reserves to prepare for disasters. On the other hand, HO#1 generally prefers to maintain its own reserves, as manufacturer reserves do not bring significant cost advantages, possibly due to geographical distance.

Table 2: Results under different objective weights

		HO's storage capacity	MFR's storage capacity	Time optimization ratio	Cost optimization ratio
Situation 1 $wt = [0.8,0.2]$	HO#1	4847	4848	0.654615	1.20357
	HO#2	0	2355	0.596359	0.7828
	HO#3	4854	6575	0.871713	0.885755
Situation 2 $wt = [0.6,0.4]$	HO#1	4779	4904	0.698091	1.20033
	HO#2	0	0	0.683352	0.193627
	HO#3	4852	6539	0.871251	0.879845
Situation 3 $wt = [0.4,0.6]$	HO#1	4811	2532	2.38182	0.686181
	HO#2	0	0	1.87847	0.945397
	HO#3	4903	4874	0.750246	0.900753
Situation 4 $wt = [0.2,0.8]$	HO#1	4685	0	2.56049	0.770168
	HO#2	0	0	1.61749	0.95978
	HO#3	4737	4995	0.830541	0.620328

5.3. Subsidy Impact on Cooperation

The subsidy mechanism has been specifically applied in regional cooperation in China, effectively reducing the costs for the aid providers. To explore the mechanism's concrete value, a scenario without subsidies was set as a control group, with the results shown in Table 3. The larger the value in the table, the worse the optimization effect of that stakeholder compared to the others. By calculating the variance in both scenarios, it is clear that the subsidy mechanism significantly alleviates the imbalance of profits. The average variance in the time dimension decreased by 9.5%, while the average variance in the cost dimension decreased by 62%. From the perspective of each stakeholder's performance, HO#3 does not achieve much objective optimization without subsidies and played the role of a contributor. HO#2 has the highest level of profit, but this decreased under the influence of the subsidy mechanism.

Table 3: The impact of subsidies on the objectives of each stakeholder

	$\frac{F_a(h)}{AT_h} / \sum_{h \in H} \frac{F_a(h)}{AT_h}$		$\frac{F_b(h)-PI_h+PO_h}{AC_h} / \sum_{h \in H} \frac{F_b(h)-PI_h+PO_h}{AC_h}$	
	$pm = 0$	$pm \neq 0$	$pm = 0$	$pm \neq 0$
HO#1	0.310633	0.312537	0.349508	0.366342
HO#2	0.284422	0.286621	0.22539	0.245083
HO#3	0.404946	0.400842	0.425102	0.388575

6. Conclusions

The humanitarian assistance chain proposed combines horizontal and vertical cooperation. Research indicates that cooperation can save 8.6% of costs and reduce rescue time by 10.7%. For each stakeholder, cooperation is beneficial in optimizing their own objectives. The post-disaster transportation compensation mechanism can significantly reduce the imbalance of benefits, avoiding the emergence of absolute beneficiaries, which could otherwise affect the optimization of interests for other stakeholders. In vertical cooperation, the inclusion of manufacturers not only alleviates risks but also offers lower costs. For certain regions, it can serve as a preferred option. These findings help countries or provinces develop regional disaster strategic planning. Senior managers need to determine the main directions of supply flow within the network and clarify the roles of each stakeholder. It also helps to clarify the expression of benefits under cooperation, enhance stakeholders' awareness of cooperation, and thus strengthen their willingness and actively take action.

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