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The regional cooperation-based warehouse location problem for relief supplies

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ABSTRACT

Regions often cooperate with each other in emergency rescue efforts, often times maintaining the principle of territorial priority. In this paper, a regional cooperation-based relief warehouse location model is constructed that takes into consideration the principle of territorial priority. The objective of the model is to minimize the maximum expected cost of any region. Problems of different size are tested in numerical experiments. Results show that regional cooperation can significantly reduce the maximum expected cost of any region. Then, a case study of the relief warehouse location problem in the Northern Beijing area is demonstrated for the storage of disinfectants to be used in case of large-scale flooding. The expected cost in the pre-disaster planning and the efficiency of the rescue efforts during the disaster are both taken into account. A suitable value of the upper limit for the transport time is obtained. The work of this study verifies the usefulness of considering both territorial priority and regional cooperation in emergency management.

1. Introduction

Many people are affected by disasters every year. In 2016, about 137 million people were affected by disasters in China as of July 26, especially in the middle and down regions of the Yangtze River. From June 27 to July 4, there were more than 18 million people affected in the Provinces of Anhui and Hubei. Their survival depends on disaster relief assistance. The national level supplies delivered emergency supplies to the affected regions, including tents, folding beds, bedding and so on. Disaster relief work was important in overcoming the loss of life and damages. Effective rescue planning helps to reduce life and property loss, to protect basic livelihoods and to improve a government's reputation. However, because of inappropriate warehouse locations, some emergency supplies cannot reach the disaster area in time, and some emergency supplies are wasted.

Many emergency management agencies have focused on the warehouse location problem of emergency supplies. For example, the Centers for Disease Control and Prevention (CDCP) are entrusted with the task of establishing the Strategic National Stockpile (SNS). Medicines will be delivered to any state in the United States within 12 h of the SNS being needed. The Foreign Disaster Assistance Office (OFDA) has been established for international relief by the United States. There are seven warehouses for emergency supplies in the world. The OFDA will send rescue supplies to the disaster area from the nearest warehouse if it is needed. In China, the Ministry of Civil Affairs has built ten central warehouses for emergency supplies. Relief supplies will be transported to the affected areas when a disaster occurs.

Emergency management is administered under the principle of territorial priority. Emergency rescue is a complex work that needs a detailed understanding of each region. The Law of the People's Republic of China on Response to Emergencies has emphasized that the territorial priority principle should be applied in emergency management. This law requires emergency managers to be responsible for emergencies in their jurisdictional region. The emergency management system in the United States has also mentioned the territorial priority principle. The National Incident Management System has emphasized that most incidents are managed locally. Emergency managers need to reserve emergency supplies before a disaster occurs and to operate the relief efforts during disasters. However, no research to date has provided

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guidance regarding the regional cooperation under the territorial priority principle.

The problem of regional cooperation is studied under the territorial priority principle in this paper. There is no government, at the local, state or federal, that has all of the resources to respond to all disasters because of the uncertainty of disasters, and interstate cooperation is more efficient than states operating alone in disasters. The Emergency Management Assistance Compact (EMAC) in the United States is a law for emergency management cooperation among the states. EMAC is a basic institutional framework for the state's emergency management cooperation. States can integrate and transfer resources between all regions rapidly and orderly, according to the severity of the disaster. EMAC achieved large-scale rescue supply allocation during hurricanes Katrina and Rita. More than 60,000 rescue workers from 49 states participated in the rescue efforts. This rescue work illustrated the necessity of cooperative rescue efforts among the regions for a sudden cross-border disaster. During a disaster, governments strive to cooperate. However, governments seldom consider cooperation regarding the emergency supply reserve between the regions before a disaster occurs.

A regional cooperation-based emergency supply reserve model cannot only reduce the cost for each region but also can improve the efficiency of the rescue efforts during a disaster. For example, there may be a region that needs little supply possibly due to being in a low population density area and has low likelihood of an emergency occurring in that region, and without cooperation a warehouse may still need to be built and located in the region. However, in the case of regional cooperation, supplies for this region could be stored in a warehouse of another region for some compensation. This could possibly benefit both regions. For another example, there may be a demand point in a region which is close to demand points of another region, and regional cooperation could possibly reduce the transport cost and time.

A regional cooperation-based emergency supply warehouse location model is established in this paper. A scenario-based method (Verma & Gaukler, 2014) is used to address the uncertainty of the disaster. A disaster impact function is developed to measure the impact of the disaster. Compensation is employed to promote regional cooperation under the territorial priority management principle. Numerical experiments analyze problems of different size. Finally, we provide a flooding example in the northern areas of Beijing to study the best locations for the warehouses.

The remainder of this paper is organized as follows. In Section 2, we present an overview of the existing literature. Section 3 provides a formulation of the location problem that considers regional cooperation under the territorial priority management principle. Section 4 provides numerical experiments of our model. Section 5 concludes the paper.

2. Literature review

The literature review of this paper covers three areas: the emergency facility location problem, the emergency management cooperation problem, and disaster evolution.

The facility location problem is a classical problem in operations research and management science. The emergency facility location problem typically has more uncertainty than the traditional location problem. Church and ReVelle (1974) proposed the maximum coverage location problem. The researchers noted that the model was suitable for the fire station location problem and the ambulance dispatching station location problem. Gendreau, Laporte, and Semet (1997) proposed a multi-level coverage model to solve this problem. Ukkusuri and Yushimito (2008) adopted the covering method for the emergency supply warehouse location problem before a disaster occurs. The researchers maximized the probability that the demand can be at least covered by one warehouse. Chanta, Mayorga, and McLay (2014) studied the ambulance dispatching station location problem and considered that the traditional coverage model is suitable for densely populated areas but not for sparsely populated areas. The researchers proposed an optimization model that strives to achieve three objectives to consider both rural and urban areas to balance the response time of the ambulance. Farahani, Hassani, Mousavi, and Baygi (2014) proposed a hierarchical location problem. The researchers presented a real-life case of a health centers location problem in a metropolis in the Middle East. The researchers considered the possibility of failure in the health centers according to the disasters that have occurred in recent decades. Unluyurt and Tuncer (2016) proposed a simulation based methodology to evaluate Emergency Medical Service location models. In the above literature, emergency facilities always belong to a region. Each facility can be used by any demand node in the region. However, sometimes cooperation between regions may be required to effectively manage the distribution of the emergency supplies during a disaster. Emergency supplies may be needed from nearby regions. We study a problem where supplies that do not belong to the affected region could be used, but compensation must be paid to the region that the supplies are located in order for the affected region to use them. This feature of our model is one difference from the previous literature.

Researchers have used scenario based methods to address the uncertainty of disasters in the facility location problem. These researchers selected emergency supply reserve facilities by considering all possible disasters that may occur. Jia, Ordonez, and Dessouky (2007) considered disasters of the same type as a scenario in the facility location problem for medical supplies. Balcik and Beamon (2008) studied a scenario-based emergency supply warehouse location problem. They believed that demand, transportation cost and time may vary for the different scenarios. Duran, Gutierrez, and Keskinocak (2011) established a model for the emergency supply warehouse location problem, in which the scenarios are divided by demand. The model is helpful for the international organization, CARE, in determining their facility network and supply allocation. Verma and Gaukler (2014) assumed each node can be a disaster center, and each center has a potential disaster. This scenario-based method is used in our paper but with some differences. Our model uses a disaster impact function to assess the extent of influence on the demand and the time delay. The function is based on the vulnerability of the disaster center as well as the distance from the center to the affected points.

Disasters often cause great damage to society. Many articles have noted that a disaster will decrease the facility's original capacity. Jia et al. (2007) considered the capacity loss of facilities in the emergency facility location problem. Additionally, a fixed capacity loss rate of each facility for each scenario was established. The lost capacity is not available once the disaster occurs. Paul and Batta (2008) also considered the loss of hospital capacity for the hospital location problem in a disaster. Verma and Gaukler (2014) believed that the loss of facility capacity is determined by the distance from the disaster center in the emergency facility location problem. Our paper is based on this idea. That is, the demand of a node is determined by the distance to the disaster center. The difference is that Verma and Gaukler (2014) do not consider the impact of the disasters on the transport time. In most disasters, roads in the disaster area are damaged. Therefore, our model assumes that both demand and transport time are affected by a disaster.

Regional cooperation can improve the efficiency of the rescue work effectively in emergency management. Kapucu, Arslan, and Collins (2010) studied the response of the government to hurricanes Katrina and Rita and found many problems with the cooperation among the states during the relief efforts. The researchers suggested that the investment in community capacity at the local and state level should be increased and the cooperation among local, state and federal agencies of the resources should be considered. Tatham and Kovacs (2010) studied the trust problem of the humanitarian aid supply network that logistic members had among themselves from multiple organizations and developed an agile trust model. Hackl and Pruckner (2006) analyzed emergency rescue characteristics of the Red Cross in Austria from the perspective of supply and demand and provided donation policy suggestions. These studies showed the importance of cooperation among the regions in emergency management. Most of the previous research has focused on the policies of coordination among emergency organizations and not on the cooperation of the emergency supply warehouse location problem.

Most articles used disasters such as floods and earthquakes as examples to study disaster evolution. Research on the runoff and sink flow of rainstorms showed that floods were affected by land infiltration, the roughness of the land surface, the flow of the river and other aspects in the flow process (Bronstert et al., 2007; Brown, 1988; Campans & Tucol, 2001). This research indicated that the intensity of a flood is decreased with an increase in the distance of the flow. In the research of earthquake assessments, many studies examined the earthquake attenuation through the relation of the distance to the earthquake center and the intensity of Mecca (Chavez & Castro, 1988; Gupta, Chopra, Prajapati, Sutar, & Bansal, 2013; Howell & Schultz, 1975). Researchers indicated that the seismic intensity of a region is related to the distance from the region to the earthquake center. These conclusions have important implications for regionally based emergency management. The disaster impact function in our paper adopts the idea that the loss is decreased with increasing distance to the disaster center. However, the impact of a node from a disaster is related not only to the distance to the disaster center but also to the vulnerability of the node. The impact function estimates the impact of the disaster on the demand and the transport time.

Many articles have recognized the importance of regional cooperation and studied the inadequacy of regional cooperation in rescue efforts. However, few articles considered regional cooperation under the territorial priority principle in the emergency supply warehouse location problem. And, we fill this gap in the literature by studying the regional cooperation-based emergency supply warehouse location problem using a scenario based method.

3. Mathematical formulation

3.1. Problem description

In the emergency supply warehouse location problem, regional cooperation is considered under the territorial priority principle. This paper assumes that there are several regions in the area. Warehouses that belong to the area are called first-level warehouses and those that belong to the regions are called second-level warehouses. Supplies stored at the second-level warehouses belong to the region while the supplies stored in the first-level warehouses belong to the area. We assume a region pays a compensation for the supplies stored at second-level warehouses located in other regions. This is consistent with existing policies in China. Also, according to the administrative procedures on relief supplies for the central-level warehouses in China and the management method for emergency supplies issued by the provinces and cities, when the region is facing shortages of supplies, it can apply to the area for assistance. Supplies provided by the area will be free of use. Therefore, the first-level warehouses supply every region free of charge. The problem is then to find suitable locations for the emergency supply warehouses. The problem is shown in Fig. 1.

In Fig. 1, there are three regions in the area A: region *a*, region *b* and region *c*. Each region has demand nodes and second-level warehouses. Additionally, first-level warehouses are located in the area. The relationship between the warehouses and demand nodes are shown in Fig. 1. When there is a disaster, the demands of d_{a1} can be supplied by the region warehouses $s_{a1},\ s_{b1},\ s_{c1}$. The first-level warehouses in the area could also supply d_{a1}.

3.2. The disaster impact function

The disaster impact function evaluates the extent that a demand node is affected by a disaster. Because there are various factors that influence the disaster diffusion, it is often difficult to describe the impact function accurately. Usually, the impact function is used to describe the general characteristics of the disaster. In general, in the affected range of the disaster center, if the distance to the disaster center is closer, the impact is greater. At the same time, the vulnerability of the disaster center and nodes in the affected range are closely related to the significance of the impact. Therefore, the impact function is described as follows.

The disaster impact function is represented by h_{ej}. The function is a distance-based function between node j and the disaster centered at node e. The formula is

$$h_{ej} = \begin{cases} \alpha_e \gamma_e \gamma_j e^{-\beta_e d_{ej}}, e \neq j, j \in A_e \\ \alpha_e \gamma_e, e = j \\ 0, j \notin A_e \end{cases} .$$

A_e is the affected range of the disaster that is centered at node e, d_{ej} is the distance between node j and the disaster centered at node e. The values of h_{ej} decrease with increasing d_{ej}. When the distance between the disaster center and the node increases, the impact of the disaster on the node is less. Parameter γ_e is the vulnerability coefficient of node e and γ_j is the vulnerability coefficient of node j. The values of h_{ej} increase when the parameters γ_e and γ_j increase. When the vulnerability coefficient increases, the impact of the disaster on the node is larger. Parameters α_e and β_e are coefficients for the function which are decided by characteristics of the disaster and the region. h_{ej} increases when the parameter α_e increases or when the parameter β_e decreases. Since the parameters are set as $\gamma_e,\ \gamma_j,\ \alpha_e,\ \beta_e \in (0,1)$, $h_{ej} \in (0,1)$.

Note that both the demand and transport time are affected by a disaster. The impact factors are shown in the following.

(1) Demand. $\tilde{D}_{ej} = h_{ej} D_j$ is used to calculate the effective demand of node j, when a disaster occurs at node e where D_j is the affected population of node j.
(2) Time. When a disaster occurs in node e, the transport time from node i to node j is expressed as $\tilde{t}_{eij} = (1 + h_{ei} + h_{ej}) t_{ij}$. t_{ij} is the transport time from node i to node j during ordinary times.

An example of the impact function is shown in Fig. 2(a) and (b). In Fig. 2(a), node *a* and node *b* are demand nodes, and node *s* is a warehouse. The demand quantity in node *a* is D_a, and the demand quantity in node *b* is D_b. The transport time from node *s* to node *a* is

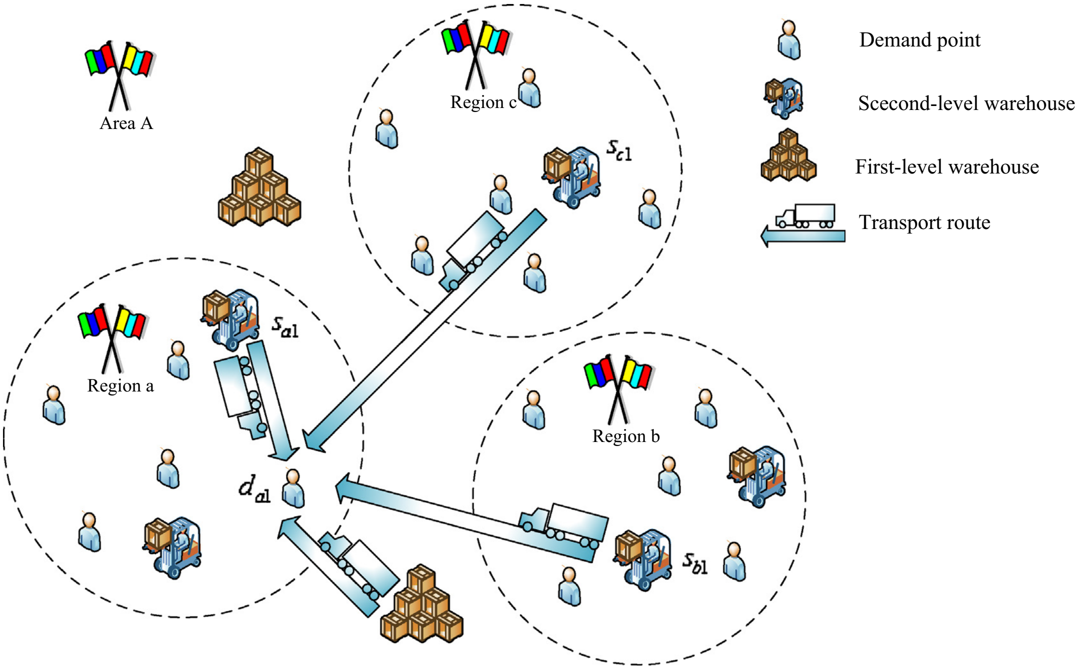

Fig. 1. Sample of regional cooperation.

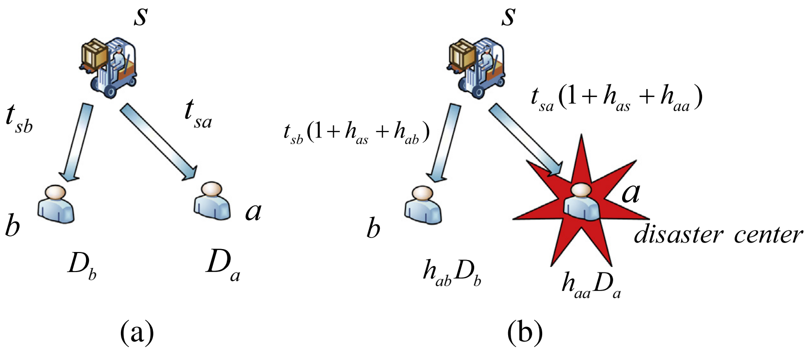

Fig. 2. (a) Before the disaster. (b) The disaster occurs.

t_{sa} and to node b is t_{sb}. In Fig. 2(b), a disaster occurs in node a, which will impact all the nodes. The demand of node a is $h_{aa}D_a$, and the demand of node b is $h_{ab}D_b$. The transport time from node s to node a increases to $t_{sa}(1+h_{as}+h_{aa})$. The transport time from node s to node b changes to $t_{sb}(1+h_{as}+h_{ab})$.

3.3. The model

At present, several regional cooperation alliances of the relief effort have been established in China. They state that members in the alliance can use the supplies which belong to other members when a disaster occurs. Appropriate compensation should be given after the disaster to use the supplies stored at other regions. However, there is a lack of models and tools that consider this form of cooperation to guide national and regional disaster planners on how best to implement a regional cooperation alliance that still maintains the territorial priority principle. This paper presents one such model that uses an appropriate compensation mechanism when cooperation is used.

We assume regions are only willing to participate in the cooperation only when the benefits are greater than the costs after cooperation. Therefore, the cost for each region must be reduced after cooperation. In cooperation, fairness among members is also a factor that needs to be considered. Thus, we use the maximum expected cost of any region as well as the area as the surrogate measure for fairness and as the objective to minimize. Trying to balance the costs is a suitable strategy when the regions are of similar size or have similar characteristics.

Because each second-level warehouse is owned by the region in which it is located, compensation to the region is needed if its warehouse is used by other regions. That is to say, if supplies of region k are stored in the warehouse of region k' , then, region k is required to give appropriate compensation to region k'. Therefore, the unit supply compensation cost is set to promote the cooperation between the regions.

The notation that is used throughout the remainder of this paper is presented next.

Parameters	
n	The number of regions in the area.
I	Potential warehouses $I = I_S \cup I_0, I_S = \{I_1, I_2, \ldots, I_n\}$, where I_0 is the set of potential locations for the first-level warehouses, I_S is the set of all second-level potential warehouses, and I_k is the set of second-level potential warehouses in region k, where $k = 1, 2, \ldots, n$.
J	Set of all demand nodes $J = \{J_1, J_2, \ldots, J_n\}$ where J_k is the set of demand nodes in region k, where $k = 1, 2, \ldots, n$.
D_j	Population of node j.
p_j	The probability of disaster occurring at node j
f_i	The cost of opening a warehouse at node $i \in I$.
c	The purchase cost of one unit of supply.
tc	The transport cost of one unit of supply per unit distance.
bc	The compensation per unit of supply.
d_{ij}	The distance from node i to node j.
t_{ij}	Transport time between node i and node j during ordinary times.
h_{ej}	Impact function of a disaster centered at node e to node j.
T	Upper limit of the transport time.
U_k	The expected cost of region k before cooperation.
U_0	The expected cost of the first-level warehouses in the area before cooperation.
Decision variables	
x_i	= 1, a warehouse is built at node i; otherwise, 0.
y_{eij}	The amount supplied from a warehouse at node i to the demand at node j if a disaster occurs at node e.
z_{eij}	= 1, warehouse at node i supplies demand at node j if a disaster occurs in node e; otherwise, 0.
W	The maximum expected cost of any region as well as the area after cooperation.
V	The maximum expected cost of any region before cooperation.

Model (A)

$$\min W \tag{1a}$$

$$z_{eij} \leqslant x_i,\ i \in I,\ j \in J,\ e \in J \tag{2a}$$

$$y_{eij} \leqslant \tilde{D}_{ej} z_{eij},\ i \in I,\ j \in J,\ e \in J \tag{3a}$$

$$\sum_{i \in I} y_{eij} \geqslant \tilde{D}_{ej},\ e \in J,\ j \in J \tag{4a}$$

$$z_{eij} \tilde{t}_{eij} \leqslant T,\ i \in I,\ j \in J,\ e \in J \tag{5a}$$

$$F_k \leqslant W,\ k = 1, 2, \ldots, n \tag{6a}$$

$$\sum_{i \in I_0} f_i x_i + \sum_{e \in J} p_e \Big(c \sum_{i \in I_0} \sum_{j \in J} y_{eij} + tc \sum_{i \in I_0} \sum_{j \in J} d_{ij} y_{eij}\Big) \leqslant W \tag{7a}$$

$$F_k \leqslant U_k,\ k = 1, 2, \ldots, n \tag{8a}$$

$$\sum_{i \in I_0} f_i x_i + \sum_{e \in J} p_e \left(c \sum_{i \in I_0} \sum_{j \in J} y_{eij} + tc \sum_{i \in I_0} \sum_{j \in J} d_{ij} y_{eij}\right) \leqslant U_0 \tag{9a}$$

$$x_i, z_{eij} \in \{0, 1\}, y_{eij} \geqslant 0,\ i \in I,\ j \in J,\ e \in J \tag{10a}$$

F_k is the expected cost of region k. The cost contains the cost of opening the second-level warehouses in the region, the purchase cost of the supplies, the transport cost and the compensation cost for using the supplies stored at second-level warehouses located at other regions, and is presented as follows.

$$F_k = \sum_{i \in I_k} f_i x_i + \sum_{e \in J} p_e \left\{ \sum_{i \in I_S} \sum_{j \in J_k} (c + d_{ij} tc) y_{eij} + \left(\sum_{i \in \{I_S/I_k\}} \sum_{j \in J_k} y_{eij} - \sum_{i \in I_k} \sum_{j \in \{J/J_k\}} y_{eij} \right) \right\},\ k = 1, 2, \ldots, n$$

In Model (A), Constraint (1a) minimizes the maximum expected cost of any region as well as the area. Constraints (2a) are the dependent constraints of the decision variables z and x. Only a selected warehouse can supply the demand. Constraints (3a) are the dependent constraints of the decision variables y and z. When z_{eij} equals to 1, the amount supplied from a warehouse at node i to the demand at node j if the disaster occurs at node e cannot be greater than the demand at node j. When z_{eij} equals to 0, $y_{eij} = 0$. Constraints (4a) require that the demands must be met. Constraints (5a) are the limits on the transport time. The transport time must be less than T. Constraints (6a) state that the cost of any region is less than W and Constraint (7a) is the same requirement but for the first-level warehouses which are owned by the area. Constraints (8a) require that the cost of each region is less after cooperation than before while Constraint (9a) is the same requirement but for the area. Constraints (10a) are the domain constraints of the decision variables.

In Model (A), parameter U_k is the expected cost of region k before cooperation where parameter U_0 is the expected cost of the first-level warehouses in the area. Before cooperation, warehouses in region k only supply the demand nodes in region k. The first-level warehouses in the area can supply all the demand nodes in the area. Parameters U_k and U_0 can be obtained using Model (B) where they become variables.

Model (B)

$$\min V \tag{1b}$$

$$z_{eij} \leqslant x_i,\ i \in I,\ j \in J,\ e \in J \tag{2b}$$

$$y_{eij} \leqslant \tilde{D}_{ej} z_{eij},\ i \in I,\ j \in J,\ e \in J \tag{3b}$$

$$\sum_{i \in I} y_{eij} \geqslant \tilde{D}_{ej},\ e \in J,\ j \in J \tag{4b}$$

$$z_{eij} \tilde{t}_{eij} \leqslant T,\ i \in I,\ j \in J,\ e \in J \tag{5b}$$

$$U_k \leqslant V,\ k = 1, 2, \ldots, n \tag{6b}$$

$$U_0 \leqslant V \tag{7b}$$

$$\sum_{e \in J} \sum_{i \in I/\{I_k, I_0\}} \sum_{j \in J_k} y_{eij} = 0,\ k = 1, 2, \ldots, n \tag{8b}$$

$$x_i, z_{eij} \in \{0, 1\}, y_{eij} \geqslant 0,\ i \in I,\ j \in J,\ e \in J \tag{9b}$$

U_k is the expected cost of region k and U_0 is the expected cost of the first-level warehouses in the area before cooperation; they are given as follows.

$$U_k = \sum_{i \in I_k} f_i x_i + \sum_{e \in J} \sum_{i \in I_k} \sum_{j \in J_k} p_e (c + tcd_{ij}) y_{eij},\ k = 1, 2, \ldots, n,$$

$$U_0 = \sum_{i \in I_0} f_i x_i + \sum_{e \in J} \sum_{i \in I_0} \sum_{j \in J} p_e (c + tcd_{ij}) y_{eij}.$$

In Model (B), the meaning of Constraints (1b–7b) is similar to Constraints (1a–7a) in Model (A). Constraints (8b) indicate that the demand in region k can only be supplied by the second-level warehouses in region k and the first-level warehouses in the area.

4. Numerical experiments

We run two sets of experiments to demonstrate different aspects of our proposed model. The first set of experiments show the performance of the models for different problem sizes. The second set of experiments determines the appropriate compensation amount for a flood emergency supply warehouse location problem in the northern regions of Beijing. The model is solved using an optimization toolbox YALMIP (Löfberg, 2004). The solver of the toolbox is CPLEX12.6 and the programming software is MATLAB 2015b.

4.1. The performance of problems of different size

Parameters are generated randomly in this section. The primary parameter settings are listed in Table 1, where $\mathrm{UI}(a,b)$ is a uniformly distributed random integer between a and b, and $\mathrm{U}(a,b)$ is a uniformly distributed random number between a and b.

In this set of experiments, problems of different size are tested. Optimal solutions of the 10 cases are obtained. Results are shown in Table 2. The number of potential warehouses and demand nodes are listed in the second column. The maximum expected costs before and after cooperation are listed in the third and fourth columns, respectively. Finally, we list the CPU time to compute the optimal solution for each experiment.

Table 2 shows the results of the 10 cases. From the results of the minimized maximum expected cost, it can be seen that the values are much less after regional cooperation. In Table 2, the percent reduction is also given, which illustrates the degree of cost reduction with regional cooperation. The results show that regional cooperation can reduce the minimized maximum expected cost and with regional cooperation the costs are better shared between the regions. That is, no one region carries an extra burden with regional cooperation and in fact all participants are ensured their costs do not increase by cooperating. As the table shows, the CPU time does increase with increasing problem size but even with large problem sizes the model can be solved within 700 CPU seconds, showing that the model can be solved effectively by the optimization toolbox YALMIP.

Table 1
Values for the parameters for the random experiments.

Parameter	Value	Parameter	Value
n	4	bc (RMB)	2
T (h)	4	P	U(0,0.6)
c (RMB)	20	D	U1(1000,3000)
tc (RMB)	0.03	f (RMB)	U1(10,000,40,000)
γ	U(0,0.8)	α	U(0.6,1)
β	U(0,0.001)		

4.2. Case study

Flooding in the Northern Beijing area is taken as an example. Floods have often occurred in this area during the past few years. In this set of experiments, we identify the most suitable value of the compensation per unit of supply for this example in Northern Beijing. Disinfectant is an essential emergency supply in flood relief work. The potential locations of the disinfectant reserve warehouses are studied. The regions are shown in Fig. 3. Major towns in each region are regarded as demand nodes. In Fig. 3, the circles represent the demand nodes, the triangles represent the second-level warehouses and the squares represent the first-level warehouses. Note there is a total of 27 potential warehouse locations. According to historical data, not every town has a potential to be flooded. Therefore, only some of the demand nodes are considered as possible disaster centers. Parameters of the case study are shown in Table 3. We asked experts in the field to set the values of the rest parameters in the model. The values of the parameters α, β *and* γ are shown in Appendix A.

The compensation cost per unit of supply, *bc*, is an important parameter in the proposed model. The analysis of the parameter *bc* is studied next for this example. The parameter is related to the purchase cost of one unit of supply. Therefore, the value of the compensation cost per unit of supply is set as $bc = mc$, where c is the purchase cost of one unit of supply and $m = 0, 0.05, 0.1, \ldots, 4$. The results are shown in Fig. 4.

Fig. 4 shows the relationship between the compensation cost per unit of supply and the minimized maximum expected cost. In the figure, the horizontal coordinate is the compensation per unit of supply, and the vertical coordinate is the minimized maximum expected cost of any region and area. It can be seen from Fig. 4 that the minimized maximum expected cost changes as the compensation cost increases. At the low values (less than 40), an increase in the compensation cost causes the minimized maximum expected cost to increase, most likely due to the fact that the increase in compensation only increases the cooperation costs without much savings. Then, at some point further increases in the compensation cost up to around 116 RMB reduces the minimized maximum expected cost. If the compensation cost increases further, the minimized maximum expected cost tends to also increase. Thus, from Fig. 4, the best value of the compensation of a unit of supply is 116 RMB, which gives a maximum expected cost of 30,823 RMB.

Table 2
Results for the different problem sizes.

Exp no.	Number of potential warehouses and demand nodes	Minimized maximum expected cost (RMB)			Elapsed CPU time (s)
		Before cooperation (×100,000)	After cooperation (×100,000)	Percent reduction (%)	
1	(19,30)	0.784	0.66	16.06	20.90
2	(16,35)	1.16	1.06	8.69	21.72
3	(23,34)	0.926	0.82	11.23	22.12
4	(22,44)	1.14	1.07	6.40	29.10
5	(25,49)	1.23	1.10	11.01	35.97
6	(24,69)	1.85	1.76	4.47	62.63
7	(34,59)	2.01	1.92	4.67	70.77
8	(27,78)	3.32	3.27	1.67	202.90
9	(28,85)	2.46	2.30	6.44	367.74
10	(23,106)	2.96	2.81	5.00	693.86

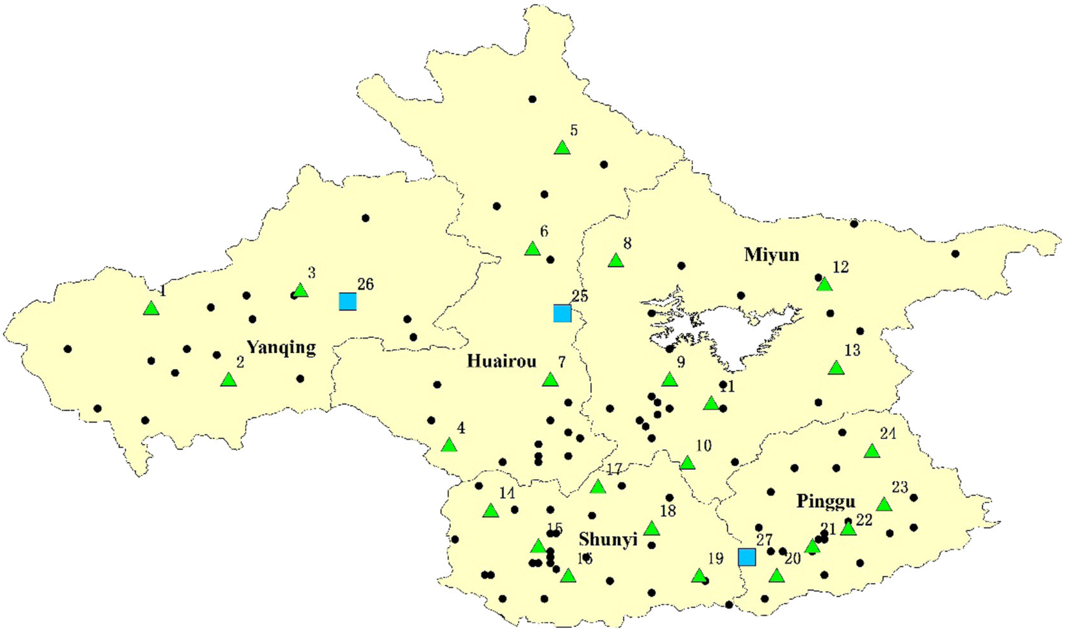

Fig. 3. The map of Northern Beijing.

Table 3
Values for the parameters for the case study.

Parameter	Value
n	5
T (h)	1.4
c (RMB)	80
tc (RMB)	1
f (RMB)	[30,000, 20,000, 24,000, 28,000, 15,000, 25,000]

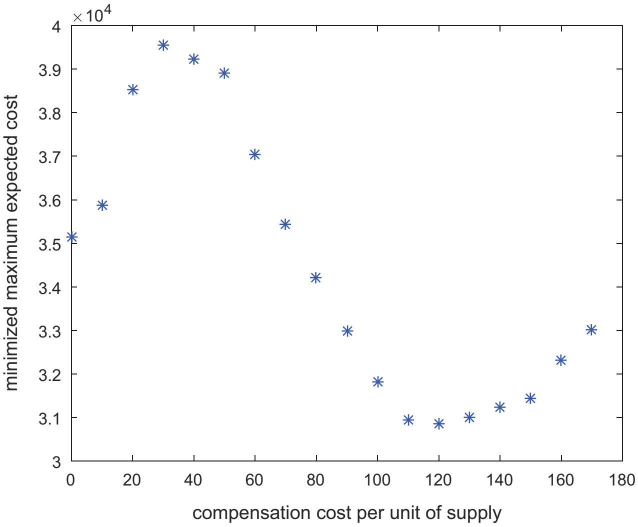

Fig. 4. Analysis of the compensation cost per unit of supply for the Northern Beijing example.

The above analysis shows the sensitivity of the unit compensation of supply with an upper limit of transport time of 1.4 h. Clearly, a smaller upper limit would ease the psychological panic of the people living in the affected areas. Thus, we next study the influence of the upper limit of the transport time on the maximum expected cost of any region and area. The best value of the unit compensation of supply changes as T changes so we also identify the best *bc* for each level of T using the same method as shown in Fig. 4. The results are shown in Table 4.

Table 4 shows the values of the minimized maximum expected cost of any region with different limits of the transport time. In Table 4, the first column shows the value of the upper limit of the transport time, the second column shows the best compensation per unit of supply for the given upper limit of transport time, the third column shows the minimized maximum expected cost of any region, and the fourth column shows the selected warehouses. As expected from Table 4, the maximum expected cost of any region increases when the upper limit of the transport time decreases. The last column shows the incremental increase of the maximum cost for each six minutes reduction in the upper limit of the response time. Based on these results, an upper limit of 1.2 h is best for this example. At these values of the upper limit there is a suitable tradeoff between cost and efficiency. With an upper limit of 1.2 h, the numbers of the selected warehouses are {2, 7, 16, 24, 25}, which are shown in Fig. 5.

In Fig. 5, a square represents a potential first-level warehouse, and a triangle represents a potential second-level warehouse; a circle represents a demand node, and a star indicates the selected warehouses. In the Yanqing district, a second-level warehouse is selected. In the Huairou district, a first-level warehouse and a second-level warehouse are selected. In the Miyun district, no warehouse is selected. In the Pinggu district, a second-level warehouse is selected. In the Shunyi district, a second-level warehouse is selected.

From the analysis above, the best values of the parameters are $bc = 484$ and $T = 1.2$. Therefore, we next compare with cooperation and without cooperation cases using these values. The results are shown in Table 5.

As the table shows, the number of warehouses is reduced by one with cooperation and the location of the warehouses also changes. With cooperation the fixed cost for no region increases. For one region it decreases to zero since it contains no warehouses, and for this region its variable costs increase since by reducing the number of warehouses (fixed cost) the region must receive its

Table 4
Results for the different upper limits of transport time.

T (h)	bc (RMB)	W (RMB)	Selected warehouses	Incremental cost (RMB)
1.4	116	30,823	3, 17, 24, 26	–
1.3	428	34,975	2, 7, 15, 24, 25	4152
1.2	484	35,111	2, 7, 16, 24, 25	136
1.1	306	35,272	1, 6, 13, 16, 26	161
1	4.2	41,115	1, 4, 6, 13, 20, 21, 25,	5843
0.9	98	42,150	1, 6, 13, 17, 24, 26	1035
0.8	76	44,509	1, 6, 13, 17, 20, 26	2359

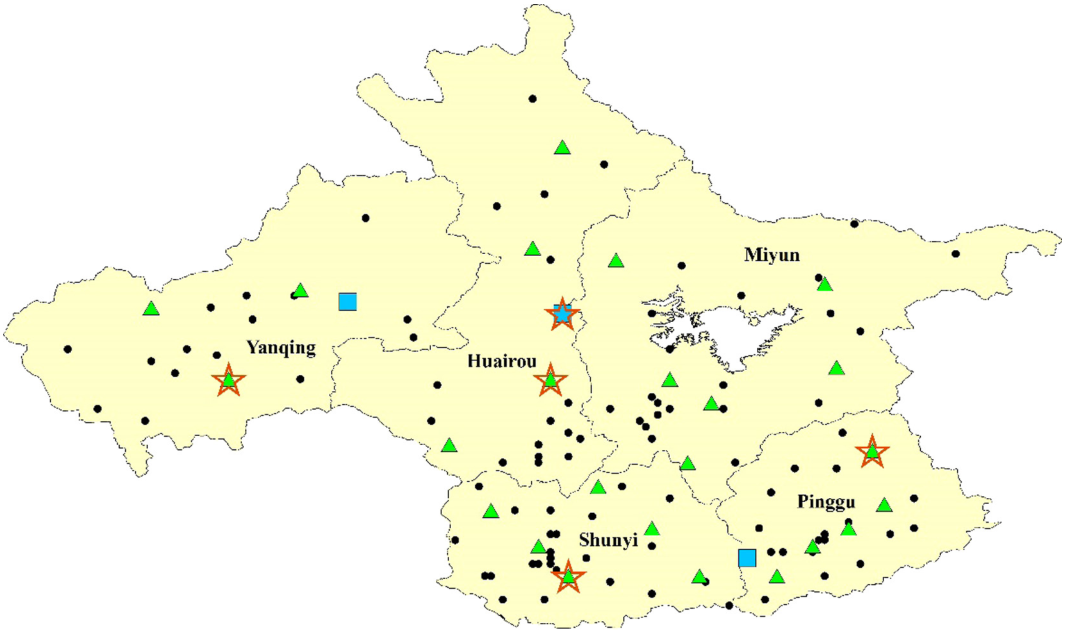

Fig. 5. Optimal emergency supply warehouse locations for the Northern Beijing example.

Table 5
Results of cooperation and no cooperation for the case study.

Results	Without cooperation	With cooperation
Locations	(2,6,13,15,24,27)	(2,7,16,24,25)
Fixed cost (×10,000 RMB)	(3.00,2.00,2.40,2.80,1.50,2.50)	(3.00,2.00,0.00,2.80,1.50,2.50)
Variable cost (×10,000 RMB)	(1.20,1.70,1.59,1.57,0.84,1.87)	(0.51,1.51,3.51,0.71,0.84,1.01)
Total cost (×10,000 RMB)	(4.20,3.70,3.99,4.37,2.34,4.37)	(3.51,3.51,3.51,3.51,2.34,3.51)

supplies from other regions which could increase its variable costs. For all other regions, the variable costs either are reduced or stay the same. Furthermore, the total cost for each region is lower with cooperation.

5. Conclusions

In this paper, the warehouse location problem for emergency supplies is studied which considers regional cooperation under the principle of territorial priority. The results in this paper are helpful to justify the rationality of regional cooperation in emergency management.

A warehouse location model for emergency supplies is developed. A scenario-based method is used to address the uncertainty of the disaster in the model. In addition, the disaster impact function is proposed to measure the impact of the node for each scenario. Fairness is considered in the regional cooperation. Therefore, the maximum expected cost of any region and the area is minimized as the objective.

The compensation per unit of supply is used as a parameter to show the cooperation among regions. The best value of this parameter is calculated for a flood example in the Northern Beijing area. The influence of the upper limit of the transport time on the minimized maximum expected cost of regions is also studied. Results show that an upper limit of the transport time of 1.2 h is suitable. The research results of this paper are helpful to provide suggestions for reserving relief supplies cooperatively in emergency management.

There are certain limitations to this paper. First, the compensation paid from one region to another is the primary basis for regional cooperation. However, in practice, the collaboration of emergency management organizations between the regions usually considers other factors such as the economic level of the regions and the ability of the national organization to enforce cooperation. Furthermore, cooperation is easier to achieve when there is sufficient supply to share but when the demand is overwhelming and there are supply shortages it is not clear how the cooperation should be formed in this scenario. Future research can consider these issues.

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Appendix A

The values of the parameters α, β *and* γ for the flooding case study in Northern Beijing are listed below.

$\gamma_i,\ i \in I$:

0.33	0.15	0.16	0.21	0.13	0.22	0.23	0.38	0.33
0.16	0.20	0.36	0.11	0.26	0.30	0.38	0.11	0.28
0.34	0.17	0.38	0.16	0.37	0.30	0.10	0.10	0.10

$\gamma_e,\ e \in J$:

0.38	0.27	0.46	0.33	0.39	0.43	0.35	0.37	0.34
0.28	0.30	0.36	0.38	0.49	0.44	0.24	0.48	0.37
0.24	0.49	0.41	0.30	0.26	0.42	0.31	0.38	0.20
0.45	0.35	0.41	0.36	0.26	0.43	0.24	0.26	0.21
0.30	0.28	0.36	0.35	0.46	0.27	0.28	0.48	0.49
0.46	0.36	0.34	0.23	0.28	0.38	0.36	0.22	0.40
0.49	0.28	0.23	0.47	0.29	0.26	0.49	0.44	0.29
0.42	0.31	0.34	0.24	0.43	0.31	0.46	0.27	0.30
0.21	0.40	0.36	0.31	0.40	0.40	0.44	0.25	0.45
0.24	0.46	0.36	0.35	0.21	0.27	0.48	0.31	0.42
0.44	0.46	0.37	0.24	0.29	0.35			

$\alpha_e,\ e \in J$:

0.61	0.89	0.00	0.00	0.62	0.00	0.98	0.85	0.82
0.98	0.00	0.91	0.00	0.85	0.00	0.00	0.00	0.00
0.00	0.83	0.88	0.00	0.87	0.00	0.00	0.00	0.75
0.00	0.61	0.00	0.68	0.00	0.00	0.74	0.66	0.95
0.00	0.00	0.00	0.66	1.00	0.68	0.61	0.00	0.00
0.00	0.73	0.00	0.00	0.78	0.00	0.00	0.66	0.72
0.82	0.00	0.00	0.63	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.97	0.00	0.00	0.00	0.00	0.80	0.74
0.00	0.00	0.00	0.70	0.00	0.70	0.00	0.00	0.86
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.77
0.00	0.00	0.74	0.00	0.00	0.00			

$\beta_e,\ e \in J$:

0.03	0.00	0.00	0.00	0.03	0.00	0.03	0.02	0.04
0.00	0.00	0.02	0.00	0.03	0.00	0.00	0.00	0.00
0.00	0.03	0.00	0.00	0.02	0.00	0.00	0.00	0.01
0.00	0.04	0.00	0.02	0.00	0.00	0.03	0.02	0.04
0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00
0.00	0.01	0.00	0.00	0.03	0.00	0.00	0.01	0.02
0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.04	0.03
0.00	0.00	0.00	0.04	0.00	0.04	0.00	0.00	0.04
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
0.00	0.00	0.02	0.00	0.00	0.00			

References

Balcik, B., & Beamon, B. M. (2008). Facility location in humanitarian relief. *International Journal of Logistics, 11*(2), 101–121.

Bronstert, A., Bardossy, A., Bismuth, C., Buiteveld, H., Disse, M., Engel, H., ... Ritter, N. (2007). Multi-scale modeling of land-use change and river training effects on floods in the Rhine basin. *River Research and Applications, 23*, 1102–1125.

Brown, R. G. (1988). Effects of precipitation and land use on storm runoff. *Water Resources Bulletin, 24*, 421–425.

Campans, N. A., & Tucol, C. E. M. (2001). Predicting floods from urban development scenarios: Case study of the Diiuvio Basin, Porto Alegre, Brazil. *Urban Water, 3*, 113–124.

Chanta, S., Mayorga, M. E., & McLay, L. A. (2014). Improving emergency service in rural areas: A bi-objective covering location model for EMS systems. *Annals of Operations Research, 221*(1), 133–159.

Chavez, M., & Castro, R. (1988). Attenuation of modified Mercalli intensity with distance in Mexico. *Bulletin of the Seismological Society of America, 78*(6), 1875–1884.

Church, R., & ReVelle, C. (1974). The maximal covering location problem. *Papers in Regional Science, 32*(1), 101–118.

Duran, S., Gutierrez, M. A., & Keskinocak, P. (2011). Pre-positioning of emergency items for CARE international. *Interfaces, 41*(3), 223–237.

Farahani, R. Z., Hassani, A., Mousavi, S. M., & Baygi, M. B. (2014). A hybrid artificial bee colony for disruption in a hierarchical maximal covering location problem. *Computers & Industrial Engineering, 75*, 129–141.

Gendreau, M., Laporte, G., & Semet, F. (1997). Solving an ambulance location model by tabu search. *Location Science, 5*(2), 75–88.

Gupta, A. K., Chopra, S., Prajapati, S. K., Sutar, A. K., & Bansal, B. K. (2013). Intensity distribution of M 4.9 Haryana-Delhi border earthquake. *Natural Hazards, 68*(2), 405–417.

Hackl, F., & Pruckner, G. J. (2006). Demand and supply of emergency help: An economic analysis of Red Cross services. *Health Policy, 77*(3), 326–338.

Howell, B. F., & Schultz, T. R. (1975). Attenuation of modified Mercalli intensity with distance from the epicenter. *Bulletin of the Seismological Society of America, 65*(3), 651–665.

Jia, H., Ordonez, F., & Dessouky, M. M. (2007). Solution approaches for facility location of medical supplies for large-scale emergencies. *Computers & Industrial Engineering, 52*(2), 257–276.

Kapucu, N., Arslan, T., & Collins, M. L. (2010). Examining intergovernmental and inter-organizational response to catastrophic disasters: Toward a network-centered approach. *Administration & Society, 42*(2), 222–247.

Löfberg, J. (2004). YALMIP: A toolbox for modeling and optimization in MATLAB. In *Proceedings of the CACSD conference, Taipei, Taiwan, 4 September* (pp. 284–289).

Paul, J. A., & Batta, R. (2008). Models for hospital location and capacity allocation for an area prone to natural disasters. *International Journal of Operational Research, 3*(5), 473–496.

Tatham, P., & Kovacs, G. (2010). The application of "swift trust" to humanitarian logistics. *International Journal of Production Economics, 126*(1), 35–45.

The Emergency Management Assistance Compact (EMAC) Website. Emergency Management Assistance Compact. http://www.emacweb.org.

Ukkusuri, S. V., & Yushimito, W. F. (2008). Location routing approach for the humanitarian prepositioning problem. *Transportation Research Record: Journal of the Transportation Research Board, 2089*(1), 18–25.

Unluyurt, T., & Tuncer, Y. (2016). Estimating the performance of emergency medical service location models via discrete event simulation. *Computers & Industrial Engineering*. http://dx.doi.org/10.1016/j.cie.2016.03.029.

Verma, A., & Gaukler, G. M. (2014). Pre-positioning disaster response facilities at safe locations: An evaluation of deterministic and stochastic modeling approaches. *Computers & Operations Research, 62*, 197–209.