Approach for the spatio-temporal diffusion process and path model of disaster system

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Abstract. The diffusion-oriented disaster system in spatial-temporal networks can be used to excavate the chain relationship between disaster nodes for using the similar space vectors. A methodological approach to analyze the vulnerability of interdependent infrastructures has been introduced. In this paper, the main purpose is to develop the diffusion process and path model of disaster system. Based on spatial-temporal factors, a model for identification of risk of a region is built. It describes the relationship between distance and time in the diffusion process of disaster system. Furthermore, to demonstrate the path of disaster spreading using the improved algorithm of the ant colony. The results show that the diffusion of disaster system is a typical spatial-temporal unified diffusion process, the space distance can hinder the spread of the disaster, and the number of the affected nodes in the region is a negatively exponential relationship with the distance factor. The application of ant colony optimal algorithm to the research of disaster diffusion path has high accuracy and practicability.

1. Introduction
With the frequency increase of natural disasters, in recent years, it leads to a serious loss of economy and society [1]. In the current research, the natural disaster risk is defined by the following relationship [2]:

Natural disaster risk = f (Hazard and Vulnerability)

Where Hazard D= f (extension frequency, magnitude {strength of event}), Vulnerability D= f (physical, social, economic and environmental factors).

Obviously, pure natural disasters do not exist, it is a natural physical system internal interaction with social consequences, and points out that the disaster has evolved diffusion characteristics [2]. At present, the most widely and maturely applied methods are the probability description based on using the fuzzy set theory of risk analysis [3]. Rough set theory [4] is another method to deal with uncertainty. Applying the fuzzy set theory to solve the uncertainty in the risks can better cope with the inconsistency and non-uniformity of the data, the insufficiency of sample size and other problems. Neural network [5] is a modeling tool capable of handling the systems’ non-linearity and the large and composite relationships of an ideal damage assessment strategy.
To prevent the expansion of hazards caused by disasters, some researchers used the complex network transmission dynamics to study the anti-destroying ability, which lay a foundation for the study of the disaster spread [8; 9; 10]. The information diffusion model is an effective method to deal with the small-sample issue in the natural disaster analysis. It can capture complex nonlinear relationships without needing to get more knowledge about the physical processes [11]. This method can be provided a greater reliability for hazard risk assessment, disaster factor detection, and risk probability estimation [12; 13]. Most of these traditional risk diffusion control methods are based on a specific cause-and-effect logic relationship among the members, if it cannot accurately grasp the member associations on the practical application, this limits the effective application of the above methods.

The time-dependent hazard of disaster analysis method is developed based on the theory of seismic construction method, and the related research and applications are more and more widely in recent years. Existing risk evaluation is mainly based on disaster records and statistics to evaluate the harm of disaster loss. Menoni [17] is the first to suggest that the concept of disaster damage chain was replaced by the concept of disaster loss. Dombrowski believes that pure natural disasters do not exist. Worni et al. [18] puts forward the homology and chain distribution of the disaster, and has a very high value for the disaster prediction and evaluation. However, because of the diffusion problem caused by the disasters associated with space and time, it is difficult to extract the complex characteristics of the disaster association rules effectively, so the degree of efficiency and credibility may be low.

Based on the similarity matching method of time series, the correlation analysis of disaster region can be achieved, but only the correlation degree model between the general regions is obtained, and the causal relationship between regions is not determined. Obviously, the ant colony optimal algorithm is used to improve the mining speed and precision. Firstly, we build a spatial-temporal model to analyse the scenario of disaster diffusion and the disaster evolution trend of the node. The calculation model was established based on the average distance hypothesis has reached the disaster risk area spatial-temporal difference. Secondly, based on the spatial vector, it is a disaster correlation vector, which determines the chain rule of the corresponding node position.

This paper is organized as follows. Section 2 describes the methodology of diffusion. Section 3 modeling the diffusion based on the space and time. Section 4 lays out diffusion path of disaster system. Section 5 provides the conclusions.

2. A methodological approach

The risk diffusion of disasters is a chain-type system. The uncertainty of diffusion research lies in the evolution model of disaster chain, the number of nodes participating in diffusion and the cluster analysis of disasters. To construct a three-dimensional historical disaster network model, a multi-layer model based on fixed time span is proposed.
Each historical time layer distributes several disaster nodes, each node can choose to chain with a number of nodes. It can connect the same layer to the chain and also can be linked to the chain. Therefore, to determine the chain object can only rely on analysis of the entire 3-D network node distribution law. The spatial-temporal difference assessment process of disaster system diffusion should have several aspects as follows: (i) All the spread of the disaster characteristics can be modified according to the disaster type of interest. (ii) The affected nodes have a delay time in a disaster. After this period, the disaster will affect other nodes. (iii) Disaster could spread to neighboring nodes. Adjacent to different entities, diffusion probability may be different. (iv) It takes time to spread to another node after the disasters, the source node will be entered the phase of destruction. (v) The more dangerous the adjacent nodes of the disaster, the shorter the time will destroy the adjacent nodes. (vi) For each route diffusion, diffusion time could be extended by reducing barriers along the transmission speed.
Figure 2. Spatiotemporal diffusion path framework based on the scenario

2.1. Model assumption
In this section, based on the existing spread model based on the study of the change over time, made the following assumptions for disaster spread in one region:

**Assumption 1** Disaster area of defending is a single factor or interaction, mutually influence factors of multiple disasters. If the cluster contains multiple influencing disaster factors, the mutually reinforcing relationship between disaster factors can influence the spreading process.

**Assumption 2** Uniform distribution of medium spread environment. If the distribution is uneven, disasters in the spreading process of the space will be unpredictable and uncontrollable. This assumption is that to control other factors, only the effect of spatial distance on the spread of the disaster are considered.

**Assumption 3** The spread of the disaster is continuous and spread to designated area on spatial continuity. There are three forms on the spatial spread, extend the spread (on the space continuity), grade (follow the certain rank order, leapfrog type spread), displacement spread. Due to the uniform distribution of medium spread environment, the spread will not present a leapfrog type hierarchy order, so there can be spatial continuity.

**Assumption 4** Disaster spread has the Markov property, it means that the disaster spatial-temporal spread process has no memory, and the main basis is the accumulation of the affected degree of the situation and the decisions.

Based on the above assumptions, the time and distance spread model, two factors of disasters are studied and the influence of parameter change on the spreading process are quantitative analysed.

2.2. Diffusion model of disaster system
Based on the regional diffusion of disaster system the model is a process with the time and distance variable demand, it is affected by the time and space distance. Set area affected by the point N, disaster...
spread time is \( t \), and defending distance for \( l \) when the number of disaster points for \( x(t, l) \),  \( \lambda \) means the natural spread rate based on distance. Defending distance factors will influence the distance of the affected points and hinder the spread of disaster. Because of the empirical results, \( \lambda < 0 \). Based on the assumption that the distance between \( d + \Delta d \) and \( d \), using the following difference equation:

\[
x(t, l + \Delta l) - x(t, l) = \lambda x(t, l)
\]

(1)

Make the \( x(t, 0) = x(t) \), it could consider the distance, where \( x(t) \) is the function of the number of affected nodes in the regional and the time \( t \).

\[
x(t) = \frac{NN_0}{N_0 + (N - N_0)e^{-rt}}
\]

(2)

Where \( N \) is the number of potential nodes in the region, and the cumulative number of the affected nodes at the time \( t \) is \( x(t) \), \( r \) is the rate of the disaster spread based on time, \( x(0) = N_0 \), that means \( N_0 \) in the initial region node is affected.

\[
x(t, l) = x(t)e^{\lambda l} = \frac{NN_0e^{\lambda l}}{N_0 + (N - N_0)e^{-rl}} \quad (\lambda < 0)
\]

(3)

Set \( N=1000 \) nodes and the \( N_0=1 \) as the initial point, we observe the nodes that got infected with \( \lambda = -0.005 \), the rate based on time is \( r =0.02 \). The original data are distributed as shown in Fig. 3.

![Figure 3](image)

**Figure 3.** The spatial diffusion process of disaster system with time and distance change

By the figures above, the area of disaster spread is combined with time and distance, the time dimension is typical of the logistic curve model with a negative exponential of the distance dimension. In the two dimensions of time and space, the affected area of certain nodes is assumed. Due to the behaviour of area disaster spread, this disasters diffusion area is formed by multiple nodes which is the product of the disaster spread. This process of diffusion has formed the layout of spatial spread, because of the different node vulnerability, with potential difference in disaster-affected regions due to the different vulnerabilities of nodes. To eliminate the potential difference, disaster will continue to spread in the area and to reach the saturation. In one research area, not every node will be affected by the
disaster completely, but if it accumulates to a certain high level, the disaster could form secondary disasters and spread to other nodes.

3. Modeling the diffusion based on the space and time

3.1. Disaster diffusion analysis model of changing with distance

To classify input data, a model is needed to analyze the disaster diffusion with the distance factor. The overall process of the disaster spread in the region with the distance of space is as follows, which is given by Eq. (4).

\[ x(d) = N_0 e^{\lambda d} \quad (\lambda < 0) \]  

(4)

The data where the number of initial nodes is \( N_0 \) and the spread rate is \( \lambda \). Fig.4(a) shows the different disasters based on spread rate with distance, it keeps the negative exponential function based on the distance of disaster spread curve shape remains unchanged, but along with the increase of the diffusivity of absolute value curve shifts. This means that the nodes in the area near the source of the disaster are the first to be affected by the disaster, and the distant nodes will be later or not affected by the disaster. As a result, the distance can affect the rate of spread of disaster. Fig.4(b) shows when the source of the disaster is more, the diffusion curve is steeper, because the source of the disaster system has great influence on the surrounding nodes, in order to eliminate this "potential difference", the number of peripheral nodes will increase, and the diffusion will soon reach a stable state.

![Figure 4](image-url)  

**Figure 4.** Spread of disaster systems with different diffusion rate and number of disaster sources at a distance

Integral to the Eq. (4), the number of disaster-stricken nodes is obtained when the distance from the source is Eq. (5):

\[ x(l) = \int_0^l x(l)dl = \frac{N_0}{\lambda} (e^{\lambda l} - 1) \quad (\lambda < 0) \]  

(5)
Figure 5. The relationship between the number of cumulative affected nodes and the distance

This is confirmed by the results obtained as Fig. 5(a), (b), transmission source area due to factors such as vulnerability, it is more vulnerable to disasters than other regions. With the increase of distance, the rest of the nodes will be affected by the factors, such as natural environment, and social and economic situation. Combined with the adoption of certain anti-risk measures, so the rest of nodes are affected by the influence of the drop, potential disaster point and the distance between defending by the disaster with the node number is related to the negative exponent. The distance for the spread of the disasters which there exists negative influence, and based on different defense capabilities of nodes, disaster spread velocity also obviously is different. The spread of the curve is relatively steep when diffusion rate is greater. Due to a source of disaster impact, and its form around the potential difference is bigger, and the surrounding nodes in owing to eliminate the "potential difference". With the increasing number of impact nodes, at the same time the spread of diffusion will soon reach a steady state.

3.2. Disaster diffusion analysis model of changing with time

If it is considered by only the process of disaster diffusion, the diffusion velocity equation of the affected nodes at time \( t \) is as follows.

\[
\frac{dx}{dt} = \frac{rNN_0(N - N_0)}{\left[ (N - N_0) + N_0e^\alpha \right]}
\]
Figure 6. Cumulative number of affected nodes varies with time

From Fig6 (a), the affected area faced the disaster degree of uncertainty and lacked awareness of risk, so the weak ability to resist disasters. With the continued spread of the disasters, the cluster of potential difference is bigger and bigger, at this time in the region against the potential has not affected areas in the degree of risk has increased dramatically. With the increase of diffusion velocity, the disaster will have a widespread. This area is affected by the degree aggravate, disasters spreading ability reach saturation, therefore the spread of the disaster appear almost stopped. For different based on the diffusion rate of time, regional disaster diffusion to achieve saturation is needed time is different in Fig.6(b): the bigger diffusion rate of disaster system, the less time needed for saturated state, for the diffusion velocity of smaller disaster system, its spread for a long time. Moreover, different diffusion rates have different effects on the diffusion velocity. The larger diffusion rate means that the velocity changes faster, and the peak value is higher.

4. Diffusion Path of disaster system

4.1. Ant colony optimization algorithm to solve the path of diffusion

Using ant colony optimization algorithm to solve the diffusion path of disaster system [20]. Ant colony optimization (ACO) algorithm was proposed firstly to solve Traveling Salesman Problem (TSP) problem. Firstly, taking the diffusion of m nodes in the plane as an example to illustrate the basic ant colony algorithm model, the problem of m nodes is to find the shortest path through the m nodes once and finally back to the starting point.

We set n be the number of ants in the ant colony, $d_{ij}$ (i, j =1, 2, ..., m) denotes the distance between node i and node j, and $\tau_{ij}(t)$ denotes node i and node j at time t. Connect the concentration of pheromone on the line.

At the initial time, the concentration of pheromone in each path is the same. Set $\tau_0$ (C is a constant), Ant k (k =1, 2, ..., n) while exercise, according to the concentration of pheromone in each path to determine the direction of the transfer, $P_{ij}^k(t)$ represents the probability that ant k is transferred from city i to city j at time t. Its formula is shown in Eq. (7).
Here $g_{ij}$ is a domain dependent heuristic parameter, $a, b$ are parameters that weight the relative importance of pheromone trail and heuristic information, tabu_k ($k = 1, 2, ..., n$) is a set of ants $k$ have walked through the nodes. At the beginning there is only one element in tabu_k, i.e. the initial node of ant $k$. As evolution proceeds, elements are constantly increasing of tabu_k. Over time, the pheromones that previously remained on the various paths gradually disappear. The volatility is represented by the parameter $1-\rho$. At the $m$ time, the ant completes a cycle. Pheromone on each path the concentration of hormone should be adjusted according to Eq. (8).

\[
P_{ij}^k = \begin{cases} \frac{\tau_{ij}^a \eta_{ij}^b(t)}{\sum_{s \in \text{allowed}_k} \tau_{is}^a \eta_{is}^b(t)} & j \in \text{tabu}_k \\ 0 & \text{otherwise} \end{cases} \tag{7}
\]

4.2. Ant colony algorithm based on diffusion

In the search of the diffusion path, if it is a branch path, it releases the corresponding concentration of pheromone, the pheromone on the one hand, a direct impact in the son the ant on the solution of the two nodes, on the other hand it will be centered on the path to spread beyond, affect the behavior of other ants nearby, when they make them in the search for the path to greater probability in the next step to choose this path. Through this collaboration based on pheromone diffusion mode, other ants when choosing a city to choose to the interference of the optimal path will reduce, which greatly improve the convergence speed of the algorithm.

4.2.1. Pheromone diffusion model. Based on the gravity model, this paper constructs the correlation model to optimize the pheromone diffusion. The gravity model is based on the universal gravitation formula of Newtonian classical mechanics. The former has become an important model of spatial interaction. The classical gravity model is as follows:

\[
\tau_j(t + m) = \rho \times \tau_j + \Delta \tau_j
\]

\[
\Delta \tau_j = \sum_{k=1}^{n} \Delta \tau_{ij}^k, \rho \in (0, 1)
\] \tag{8}

Where $\Delta \tau_{ij}^k$ denotes the concentration of pheromone left by the $k$-th ant in the path $ij$ in this cycle, and $\Delta \tau_j$ denotes the sum of pheromone concentrations released by all ants in the loop on path $i$ to $j$.

In Eq. (9), $M_{ij}$ is something the size of the force between $i$ and $j$, $K$ is constant (gravity coefficient), $Y_i$ and $Y_j$, respectively, through the specific conditions of 'balanced'endogenous variable, usually for 'quality'of the $i$ and $j$, $D_{ij}$ for the "distance" between the two node $i$ and $j$.

We designate the target gravitational field, task area threat source repulsion field [21]. Diffusion source under the combination of attraction and repulsion, will move in the direction of the potential field force and reach the target location. Regional nodes in the gravity of the potential function and repulsion potential function are defined as respectively.
The gravitational force generated by the affected node and the repulsion of the joint defense disaster is the total potential field force.

\[ F = F_{\text{att}} + F_{\text{rep}} \]  

In the simplified pheromone diffusion model, we designed \( D_{\text{max}} \) as the pheromone diffusion of the origin. The concentration of pheromones received by the ant on the diffusion path is described in Eq. (13), and the farther from the source, the fewer pheromones the ant receives.

\[ D_c = D_{\text{max}} F \]  

4.2.2. Solution of the pheromone diffusion model. The result of the diffusion will form a circle with a gravitational field like the center of the bottom with \( i \) and \( j \) respectively. For any other node \( l \), if it is within the spread of pheromone produced by ant \( k \), the concentration of pheromone \( D_i^k \) and \( D_j^k \) produced by the ant \( k \) spread to the city can be found.

\[ \Delta \tau_{ij}^k = Q/d_{ij} \]  
\[ \Delta \tau_{il}^k = D_i^k \]  
\[ \Delta \tau_{jl}^k = D_j^k \]

Eq.(11) shows that if the ant \( k \) passes the path \( ij \) between time \( t \) and \( t+1 \), Eq.(12) indicates that if the ant \( k \) passes through the node \( i \) but does not pass through the node between times \( t \) and \( t+1 \), Eq.(13) indicates that if the ant \( k \) only passes through the node \( j \) but does not pass through the node between times \( t \) and \( t+1 \). We designate \( D_{\text{max}} = \gamma \cdot \Delta \tau_{ij}^k \) and the diffusion pheromone is centered on \( i \) and \( j \) is \( d_i \) and \( d_j \), and the Eq. (15) and (16) of a concentration of pheromone \( D_{il}^k \) and \( D_{jl}^k \) is as follows:

\[ D_i^k = \begin{cases} 
\frac{\gamma \cdot Q}{d_{il} \left( -k_a d_{i} + k_r \left( \frac{1}{d_{ij}} - \frac{1}{d_{il}} \right) \cdot \frac{1}{d_j^2} \right)} & \text{if } D_{il}^k < D_{ij} \\
0 & \text{else} \end{cases} \]  

\[ D_j^k = \begin{cases} 
\frac{\gamma \cdot Q}{d_{jl} \left( -k_a d_{j} + k_r \left( \frac{1}{d_{ij}} - \frac{1}{d_{jl}} \right) \cdot \frac{1}{d_j^2} \right)} & \text{if } D_{jl}^k < D_{ij} \\
0 & \text{else} \end{cases} \]

The ACO algorithm to solve the disaster diffusion path selection model is as follows:
Step1 Initialize the value of fundamental parameters of the ACO algorithm including the degree factor of pheromone $\alpha$, the number of ants $N$, and the degree factor of the heuristic function $\beta$. Randomly select the initial position of each ant and initial pheromone $C_i$. Calculate the new pheromone concentration on the path from node $i$ to $j$.

Step2 All ants $N$ finish path construction from the source node to the destination node.

Step3 Pheromone updating. After all the $N$ ants have finished their movement from the source node to the destination node in one cycle, the pheromone on each arc is updated with $m = 1$ of the Eq. (8).

Step4 If each ant has not completed a complete path, go to Step1; else the algorithm is terminated.

5. Computational experiments
Computational experiments are carried out on a logistics network with 12 nodes. Parameters of ACO are set as: the number of ants $M = 3$, the maximum number of cycles $N_{c_{\text{max}}} = 200$, the initial pheromone value $\alpha = 4$, $\beta = 2$, $\gamma = 0.6$, $Q = 100$, $C = 3$. When gaining coefficient of gravitational need $ka=15$ and gain coefficient of repulsion force $kr=4$, the ideal point and the weak efficient solution to the multi-objective model are shown.

From Fig.7, we can see the optimal path obtained by the algorithm, the diversity of the solution has been very good in the whole evolution, so it can obtain the new optimal solution. An improved ant colony algorithm based on pheromone diffusion is proposed and its global search ability converges very quickly in the Fig.8.

Since the disaster node is determined by the disaster center, there is a certain extent of damage and the scope may be further expanded when similar vectors are merged. The vector information has been converted to a specific location in the Fig.9.

![curve of process solution](image)

**Figure 7.** The diversity curve of the solution in solving pro
6. Conclusion
This paper studies the two factors of time and distance for disaster system. The spatial diffusion model of the change of element is established. By simulating the dynamic process of spatial diffusion, it shows that the regional disaster system is a typical spatial-temporal unified diffusion process, and emphatically analyzes the influence of the spatial distance of the regional disaster system on the diffusion of the disaster system, and the results show that the distance does affect the diffusion rate of the disaster system, Moreover, the spatial distance has a negative exponential relationship with the number of the affected nodes, and the time factor has a typical logistic curve relationship with the number of the affected nodes.

Through the establishment of the network to make 3D disasters associated analysis of the disaster is the clarity of the geographical and timescale by using ant colony algorithm by the purpose of solving the optimal path into extract high pheromone the branch of the path. This kind of improvement will greatly improve the cooperative effect between ant colonies, enhance the effectiveness of ant colony
algorithm, and the improved artificial ant colony system is more faithful to the real ant colony system in nature.

In this paper, the spatial diffusion of single disaster species in the region is studied, and the diffusion process of multiple disasters and the diffusion process of disaster system in the inhomogeneous environment will be the further research content.

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