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Research on Community Resilience Theory Based on Entropy and Self-Organization and Its Application in Decision

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Abstract. In order to improve the ability of community governance and reduce the occurrence of accidents, based on the entropy and self-organization theory, this paper first analyzes the influencing factors of community resilience, analyzes the process of emergency and the key factors of response from the change of entropy value of community security system, constructs the mathematical expression of community resilience and entropy value, extracts the evolution law of community resilience, and then constructs the decision theory of building entropy effect and improving community resilience from the perspective of input-output benefit. The results show that the community resilience is positively correlated with the absolute value of negative entropy; the community resilience is negatively correlated with the absolute value of positive entropy; the system resilience can be improved by allocating the limited degree and quantity value according to the importance of the impact on the correlation of each subsystem in the community system.

Keywords. Community Resilience Theory; Decision theory; entropy; self-organization; Mathematical representation

1. Introduction

In China enjoying a period of rapid development, there are infrastructures constructed at different times and in different spaces, which, together with the increased heterogeneity of the population, as well as the information explosion and asymmetry, have made it hard to implement risk government, and made communities more vulnerable to emergency accidents. Communities form the forefront of emergency prevention and response, while resilient communities attach more importance to risk adaptation, recovery, and learning transformation capabilities of each "cell" in the urban system [1]. In foreign countries, the concept of "resilient community" is relatively mature, which can be interpreted as the integration of a series of capabilities of a community, including internal stability [2,3], resilience [4,5], and adaptability [6-8].

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The stability and resilience of a community are passive, while the adaptability is proactive [1].

In terms of assessment on community resilience, more foreign scholars have assessed the resilience of a city based on quantitative indicators. Resilience Alliance [9] (1999) explored the main framework of resilient communities from the four aspects of governance network construction, metabolic flux, built environment and social dynamic mechanism; STANTON et al. [10] analyzed the resilience of infrastructure, system, economy and society in details; COMFORT et al. [11] believed that we should consider information technology and organizational learning; TWIGG et al.[12] particularly emphasized the involvement of multiple dimensions such as common interests, value, and behavioral structure.

Domestic scholars have also carried out sufficient studies on resilience theory, and demonstrated its application in cities. WANG Yang [13] et al. indicated that the resilience theory could make up for some shortcomings of the risk theory and make the dynamic description of risk more perfect through analyzing the relationship between risk and resilience; XU Zhaofeng et al.[14] established a cloud matter-element model with four criterion layers of infrastructure, economy, society, and organization, and improved quantitative indicators at all levels, for evaluating the level of urban resilience; HUANG Lang et al.[15] systematically analyzed the qualitative and quantitative assessment methods of system security resilience, and defined the system security resilience: The ability of a system in maintaining, recovering and optimizing system security status in the face of the impact and disturbance of risks within a certain time and space.

In summary, as for the basic units of urban society, namely the communities, the dynamic description of community risks based on the resilience theory will be beneficial to the management and control of community risks, thus reducing the occurrence of risk events; however, not many studies have been conducted regarding the in-depth qualitative research and decision support for the control of community risks. In this paper, therefore, the author studied the community resilience theory based on the idea of entropy and self-organization from the second law of thermodynamics, and explored the key points of resilience improvement strategy based on the corresponding mathematical representation.

2. Entropy and Self-organization Theory in Emergencies

2.1. Entropy and Self-organization Theory

In 1865, Clausius proposed the concept of entropy, and he believed that the entropy value would continue to increase over time in a closed system, until the “heat death”. Later, Prigogine revised the theory and proposed the Dissipative Structure Theory, which believed that any system would obtain a negative entropy flow through exchange with external energy and matter; and when the system is within a non-linear region far from the equilibrium, even if there is only a small external disturbance, the system would have large “fluctuations”. As for the forming a dissipative structure, there should be the following conditions: 1. The system must be open; 2. The system must be in a non-linear region far from equilibrium; 3. There must be certain nonlinear dynamical process in the system. According to the synergy theory, for achieving the above conditions, there must be multiple interacting subsystems that can form a self-organization structure.

2.2. Process Analysis of Emergencies Based on Entropy and Self-organization Theory

Status of the system before an emergency. Before any emergency, the entropy increase factors in the system would be superimposed; the destructive energy would aggregate and expand more rapidly; and the system would tend to be closed, linear, and nearly balanced, becoming out-of-order from order. The relatively closed status: The community organization structure is relatively closed, and some management personnel still have the traditional sense of hierarchy; the emergency linkage mechanism should be further improved; and the transmission channels of material, energy, and information are not smooth enough. The existence of linear characteristics: Although government assessment is no longer conducted based only on economy, it is still the main orientation, and the social system presents certain linear characteristics, which have resulted in certain weakness and inadequate preparation of the prevention and response mechanism of community emergencies. The near equilibrium status: In a relatively closed system with a single target orientation, if the negative entropy flow of the community system can just or cannot offset the entropy increase, the disordered development would gradually tend to near equilibrium.

Occurrence of an emergency – Breaking of the critical point of entropy increase. Both social development and organizational operation are processes of entropy increase; in the case of insufficient openness of the community system, obvious linear characteristics and blocked inflow of negative entropy flow, the system would be weak in self-organization. When the entropy increase reaches the extreme value threatening the stability of the community system, or it is affected by external crisis factors, there would be inevitable emergencies.

Reduction of emergencies and their influence – The negative entropy flows in, making internal self-organization synergetic. After an emergency, the near-equilibrium status of the community system would be broken, and the nonlinear reorganization and evolution of the system would strengthen the synergy; then the favorable external natural resources, capital forces and social governance forces would flow in, thus forming a negative entropy flow. Finally, the social system would start new, orderly and resilient operation.

2.3. First Section

It can be easily concluded through analyzing the process of the emergency and its response that the factors making the system closed, linear, and near-equilibrium should be self-inspected, so as to strengthen the self-organization and coordination capabilities, and construct an emergency prevention and control system.

1) The organizational structure of the social system should be reconstructed before any emergency. The government's function should be changed from "control" to "service", so as to construct an organizational framework with diversified governance bodies, networked governance structure, legalized governance system, and modernized governance technologies; and spread it to the grass-roots level of the society, thus breaking the linear mechanism and enhancing the openness of the system.

2) In the case of an emergency, the subsystems should improve their collaborative capacity; and the administrative departments should improve their emergency

management capability, smooth the information channels, and enhance the coordination and linkage; and reconstruct the value system of the society, to make sure that the enterprises would take the initiative to assume social responsibilities by means of source sharing, donation, and rescue in the case of an emergency. Various non-profit organizations should play their own roles in pre-prevention, immediate mutual aid, and social mobilization; the residents can also perform self-help and mutual rescue, to improve the regulating ability of the community system and synergistic effect of the subsystems, thus accelerating the anti-entropy process.

3. Community Resilience and Principle of Entropy Increase

3.1 Characteristics of Community Resilience in a Closed System

Community resilience refers to the combination of the ability of a community in control the loss within a tolerable range based on its stability in the case of an emergency, and the resilience and self-adaptability [16]. Community resilience refers to the capacity formed by the interaction of various subsystems in the community; the community security system also conforms to the principle of entropy increase. If the community security system is believed to be a closed system without material and energy exchange with the outside world, community resilience will show the following characteristics.

1) Resilience of the community physical space system. With passage of time, community buildings and urban infrastructure are gradually aging, and the environmental entropy is increasing day by day; the continuous coupling of various above-ground and underground risks would increase the physical environmental risks, and reduce the resilience of the physical space system.

2) Resilience of the community organization system. The mechanism of the community system would be gradually rigid and unable to adapt to the needs of the community from the state promoting the synergy between various subsystems and generating negative entropy flow, which will hinder the operation of the community system, greatly increase community security risks, and reduce the resilience of the community organization system.

3) Resilience of the community information system. As shown in 2), when the community organization gradually reaches a rigid state, the quick and accurate information channel will be blocked, the effective communication information cannot be accurately reported and issued, the risk of the community security system is further amplified, and the resilience of the community information system is reduced. Since people can make use of the existing resources to optimize the community system, the management entropy would play an important role in improving the community resilience.

3.2 Characteristics of Community Resilience in an Open

The community security system is not completely closed, and it would continue to exchange with the outside world, especially in the rapid urbanization process. New community infrastructures are being constructed among the old ones, and in view of the increased population heterogeneity due to the inflow of population, the organizational cohesion and communication capacities are weakened, which would increase the community security risks; at the same time, the community can also improve the resilience by taking various strategies. For example, the community can reinforce the housing to resist earthquakes and build disaster prevention projects to improve disaster resistance; enhance the networking and diversification of community organization, to improve stability and coordination; reconstruct social values, strengthen the subjective willingness of self and mutual aid; clear the information communication and release channels, and improve the efficiency and accuracy of information circulation. However, due to the limited social resources, it is imperative to clearly understand the quantitative relationship between various factors of community resilience, and optimize the resilience improvement strategy.

4. Mathematical Representation of Community Resilience

The entropy value of the community security system would conform to certain mathematical laws under the interaction of various subsystems. At any moment, the smaller entropy value would indicate the greater total energy of the system. The total energy of the system can be taken as the function of entropy, and the resilience of the community security system can be expressed by entropy.

4.1 Representation of System Entropy

Assuming that the community security system is closed, it would conform to the second law of thermodynamics; at the same time, the management entropy would be generated by people, and the entropy of the closed community system can be expressed by the following equation:

$$\mathrm{S}_1(\mathrm{t}) = \sum_{i=1}^{n} S_{1i}\,(\mathrm{t}) = \sum_{i=1}^{n} [S_{1is}(\mathrm{t}) - S_{1im}] \tag{1}$$

Where, i refers to community security subsystems, such as the subsystems of physical space, organizational structure, social environment, economic operation, information communication, and population. $S_{1i}(t)$ is entropy value generated by each subsystem, $S_{1is}(t)$ is the pure material system entropy, and S_{1im} is the internal management entropy of the subsystem.

But the community security system is open, and it would get negative entropy flow S_e from the outside. The calculation equation of system entropy:

$$S_i(\mathrm{t}) = S_{1i}(t) - S_e \tag{2}$$

According to the Boltzmann's entropic equation, the entropy of each subsystem can be calculated:

$$\mathrm{S_i(t)} = -\mathrm{K_B} \ln \mathrm{P_i} \tag{3}$$

$\mathrm{K_B}$ is the weight of the subsystem, $\mathrm{P_i}$ is the macroscopic state quantity, which is expressed by the functional completeness of the subsystem, $\mathrm{P_i} \leq 1$.

When state 1 is changed to state 2 under sudden entropy increase $\Delta S_i(t)$, the following Boltzmann's entropic equation can be used:

$$\frac{P_{i2}}{P_{i1}} = e^{-\Delta S_i(t)/K_B} \tag{4}$$

Equation (4) can reflect the relationship between entropy and recovery of the system function completeness.

4.2 Representation of Total Energy of the System

According to Clausius and Boltzmann's entropic equations, the energy of degradation is positively associated with entropy; in the process of small changes, the total energy of the subsystem can be expressed by the function $Q_i(S_i(t))$.

$$\mathrm{d}Q_i(S_i(t))/_{P_i} = dS_i(t) \tag{5}$$

After differential equation deformation of equation (5), the integral of t at both ends can be substituted into equation (3), and the following equation is obtained:

$$Q_i(S_i(t) = \int e^{-S_i/K_B}\, \dot{S_i}(t)dt \tag{6}$$

As shown in equation (6), when the entropy is negative, the larger the absolute value of the negative entropy is, the faster the energy increase rate will be; while when the entropy is positive, the energy of the system will decrease slowly, and tend to 0.

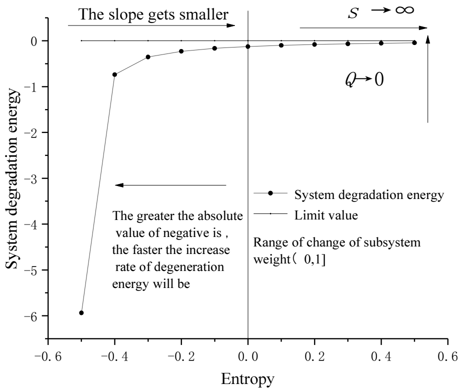

Figure 1. Change curve of entropy and system degradation energy

4.3 Mathematical Representation of Resilience of the Community Security Subsystem

As shown in figure 1, at t_0, when the system is subject to the external disturbance with entropy increase of S_0, an emergency takes place, and the total energy of the system decreases; S_0 will be allocated to each subsystem based on Equation (1) $S_0 = \sum_{i=1}^{n} K_i \Delta S_i$. The entropy increase continues to enlarge over time, and under the combined action of internal and external forces, at t_{1i}, the entropy increase is the greatest, and the system energy is the lowest; later, the system would gradually recover; t_{2i} indicates that the subsystem i recovers to a new state. The resilience of the community security system can be expressed as R:

$$\mathrm{R}_i = \int_{t_0}^{t_{2i}} \int e^{-S_i(t)/K_B}\, \dot{S_i}(t)dtdt \tag{7}$$

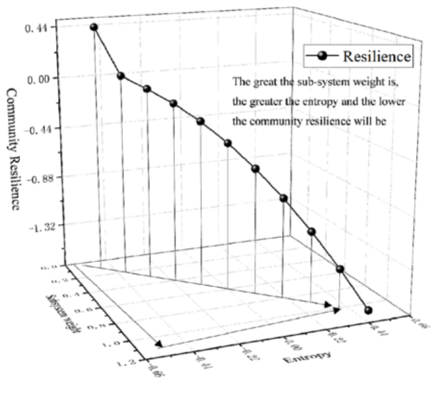

Figure 2. Sub-system weight, entropy and community resilience

4.4 Mathematical Representation of Resilience of the Community Security System

As shown in figure 2, in view of the interaction effect between different subsystems, R_S is introduced to express the interaction effect between different subsystems:

$$R_S = g(R_1, \cdots, R_i, \cdots, R_n) \quad (8)$$

5. Evolutionary Law of Community Resilience

5.1 Positive Correlation between Community Resilience and the Absolute Value of Negative Entropy

As shown in Equations (6) and (7), before an emergency, if the absolute value of negative entropy is larger, the total energy of the system would be higher. In the case of an emergency due to sudden entropy increase, the negative entropy would suddenly drop and there would be the following conditions:

1) The community system is still maintained at the level of negative entropy. At this time, the total energy of the system is reduced, but the negative entropy flow would be rapidly generated, and the system far from equilibrium would have huge "fluctuations", which can quickly offset the positive entropy; the total energy of the system would quickly drop to the bottom, the functions of the system would be recovered, in which case, the system has strong adaptability, with relatively high resilience.

2) The community system is changed to the level of negative entropy. The negative entropy flow generated by the system cannot quickly offset the positive entropy, and the energy would reach the lowest point after a long period of time. Later, it would be slowly recovered; when the entropy value becomes 0, the recovery is accelerated, and at this time, the system resilience is relatively low.

If the negative entropy flow is introduced into the system stated in 1), the system energy recovery would be multiplied; if not, the system would also be rapidly recovered. If the negative entropy flow is introduced into the system stated in 2), to prevent the entropy from becoming positive, the system would be recovered like the system in 1); however, if the negative entropy flow cannot be timely introduced, system recovery would be slowed down. The community system resilience is positively correlated with the absolute value of negative entropy.

5.2 Negative Correlation between Community Resilience and Absolute Value of Positive Entropy

As shown in Equations (6) and (7), before an emergency, if the absolute value of positive entropy is larger, the total energy of the system would be smaller. In the case of an emergency due to sudden entropy increase, the positive entropy would suddenly increase and the system would generate negative entropy, which, however, cannot offset the entropy increase; the total energy of the system would continue to decline in a long period of time, which means that there is relatively low system resilience.

If no negative entropy flow is introduced into such a system, it would gradually head to "heat death"; if the entropy value can be 0 or negative after introduction of the negative entropy flow, the system can realize a virtuous cycle. Community resilience is negatively correlated with the absolute value of positive entropy.

5.3 Influence of Optimal Allocation of Negative Entropy Flow on Resilience in the Recovery Phase

Different emergencies have different influences on various subsystems of the community; the order and size of the negative entropy flow introduced in each subsystem would inevitably affect the recovery of system functions, thus affecting the system resilience. For example, people form the most critical factor in the community system, if the emergency has a great impact on people, the negative entropy flow should be first introduced into the subsystem of people (rather than the subsystem of physical space), for rescue and allocation. Upon introduction of the negative entropy flow, the allocation based on limits and values should be made according to the importance of the influence on subsystem association, which can improve the system resilience.

6. Influence of Input-output Benefit Analysis on Community Resilience Improvement Decision

The mathematical representation of community resilience based on entropy can reveal the law of changes in community resilience, and can also be of guiding significance in the decision of community resilience improvement.

As shown in Equation (7), there can be multiple community resilience improvement strategies with different effects, but the improvement rate of the same strategy is decreasing over time: When a new strategy is initially implemented, the community resilience can be obviously improved, but as time goes on, and in view of the changes in various internal and external conditions, the improvement effect would be gradually decreased; therefore, the community should timely change its strategy; otherwise, it would waste the limited resources. However, it is very important to determine the time for changing the resilience improvement strategy.

Two concepts are introduced in this paper, namely the marginal entropy and marginal negative entropy, which are used to find the highest point of benefit in the implementation of the resilience improvement strategy based on marginal benefit. In the process of improving the resilience of the community security system with a certain strategy, if the marginal entropy of the community security system is equal to the absolute value of the marginal negative entropy ($\frac{|dse|}{|dt|} = \frac{|ds1|}{|dt|}$), it means that the increase rate of positive entropy in the system is equal to that of negative entropy, and this is the best time for strategy improvement. Because the negative entropy or management entropy is the highest at the beginning of the improvement of the physical system and organizational system of the community security system; the system would be out of equilibrium with the introduction of the negative entropy flow, and the dissipative structure plays a leading role. As time goes by, the entropy value of the community security system would be gradually increased, and the negative entropy flow generated by the dissipative structure would be gradually decreased; when the marginal entropy is equal to the marginal negative entropy, the resilience enhancement strategy would have the highest efficiency, and this is also the critical point of efficiency decrease. Therefore, it is the best time to change the resilience improvement strategy, with the lowest cost and the highest efficiency.

7. Conclusion

- This paper, based on the second law of thermodynamics and the dissipative structure theory, analyzes the process of an emergency, and constructs the community resilience theory based on entropy and self-organization.
- It completes the mathematical representation of community system energy and community resilience with the Clausius and Boltzmann's entropic equations from the concept of resilience.
- It also summarizes and sorts out the law of community resilience through analyzing the mathematical expression equation of community resilience, and analyzes the maximum input-output benefit from the perspective of marginal benefit, thus proposing the best decision-making time for improving the community resilience improvement strategy.

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