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Quantitative Analysis of Urban Logistics Resilience Based on Functional Curves

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ABSTRACT

At present, the quantitative research on the toughness of urban logistics system is still less, this paper analyzes the evolution of toughness theory and related scholars on the basis of the definition of urban logistics toughness, summarizes the quantitative research on toughness when scholars focus on the toughness of the robustness, rapidity and recoverability and other characteristics; the connotation of the toughness of the urban logistics system is summarized, and analyzes the resistance capacity of the toughness of the urban logistics system, The connotation of urban logistics system toughness is summarized, and the resistance, adaptation and recovery capacities of urban logistics system toughness are analyzed; on this basis, the function curve is combined with urban logistics research, and the functions of the urban logistics system and its function changes after the impact are characterized based on the function curve; the recovery of function curves of different logistics systems are enumerated; and a model for the assessment of the toughness capacity of the urban logistics system is constructed to build an analytical framework for the representation of the functions of the urban logistics system.

KEYWORDS: *urban logistics system; functional curve; resilience*

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INTRODUCTION

Logistics plays an indispensable role in the process of urban development. Its importance lies in that it can provide key support for people's livelihood, provide sufficient impetus for urban development, and then become the foundation of urban social development. But with the continuous development of logistics, the complexity of urban logistics system is becoming more and more prominent. In the complex urban logistics network, any uncertainty factor may bring great influence to the urban logistics system. How to maintain the vitality of urban logistics system and provide sustainable and stable logistics services for the city has become an urgent problem to be solved. In this context, "logistics resilience", as a new direction of urban logistics development, aims to improve the stability of logistics systems in coping with various uncertainties, as well as the ability to adapt, recover and improve, and has attracted the attention of some scholars. However, most scholars' current studies on logistics resilience draw on or derive from urban resilience, economic resilience and other fields. In the understanding and description of logistics resilience, they focus on describing the characteristics of resistance, recovery, adaptation and improvement shown by logistics resilience as a kind of ability, and there is still a lack of quantitative analysis on the resilience of urban logistics system and the mechanism analysis after its impact.

In terms of quantitative research on resilience, it was originally derived from the study on earthquake resilience in the field of urban infrastructure resilience. Bruneau et al assumed that the system function was 100% before the disaster with the help of the system function curve, and compared the system function before and after the impact. The curve of the system function over time and the area covered by the horizontal axis (time) were used to characterize the system resilience. Ouyang et al. represented the resilience of the system by calculating the ratio between the area enclosed by the system function curve and the time axis after impact and the area enclosed by the system function curve and the time axis under normal conditions. Based on the analysis of the resilience characteristics, Francis et al. proposed a resilience calculation formula which considered the recovery speed, initial function level, function level after failure and time of the system. Zobel et al. visualized the resilience process by setting the relationship between loss of system function and recovery time. The basic idea of quantitative analysis and characterization of resilience by existing scholars is similar, that is, the resilience of the system is expressed by comparing the functional state of the system before and after the impact, or by the recovery time of the system after the impact. In the process of quantifying resilience, the characteristics of resilience such as robustness, rapidity and recovery are mainly considered. Robustness is the ability of the system to maintain its own function under disturbance or shock. Rapidity means the speed of system function level recovery after disturbance or shock. Resilience refers to the degree to which the functional level of the system is restored after a disturbance or shock and the time required to return to the original level or target level.

Based on the above background, this paper tries to characterize the changes of system function after the impact on urban logistics system from the perspective of "resistance, absorption and recovery to external disturbance or impact" described by engineering toughness and physical toughness, and to represent the function of urban logistics system and quantify the toughness of urban logistics system.

The connotation of urban logistics resilience

The word "resilience" originates from Latin "resilio", which means "return to the original state". Later, French and English introduced this word successively. In modern English, resilience is mostly translated as resilience and resilience in Chinese. Resilience theory was first used in materials, physics, mechanics and other disciplines to describe the resilience of objects after deformation under external forces or the ability of materials to absorb energy during deformation and fracture. In psychology, it is used to describe an individual's resilience in the face of stress and frustration. In ecology, it is used to describe the characteristics or ability of an ecosystem to maintain stability. With the deepening of research, the application of resilience theory has gradually expanded to regional economic development, urban planning, community construction and other social science fields. At the same time, scholars began to try to combine resilience theory with logistics to explore the application of resilience theory in the field of logistics. Relevant scholars' definitions of logistics resilience are shown in Table 1.

Table 1 Definitions of logistics resilience by different scholars

author	definition
XIE Si-xin (2021)	The resilience of aviation logistics refers to the resistance, adjustment and recovery ability of aviation logistics to external shocks, including system force, balance force and resilience.
YU Jinyan (2021)	From the perspective of evolution, logistics resilience can be understood as the ability of the logistics system to continuously reconstruct and develop until it is more complete and more efficient.
JIN Fenghua (2021)	Based on the theory of economic resilience, it is considered that regional logistics resilience is the resistance or recovery and improvement ability of regional logistics system when it is disturbed by external economic and natural environmental conditions.

Based on the application of the concept of resilience in different disciplines and scholars' understanding of logistics resilience, this paper holds that urban logistics resilience is the ability of urban logistics system to effectively cope with disturbance or impact caused by various uncertain factors such as emergencies, mainly manifested as resistance, adaptability and resilience. Resistance mainly refers to the ability of the urban logistics system to maintain a certain level of logistics service in the face of disturbance or impact, adaptability refers to the ability of the urban logistics system to provide a certain level of logistics service after suffering certain damage in the impact, and resilience mainly refers to the ability of the urban logistics system to restore and rebuild the logistics service level that has been lost in the disturbance or impact. The purpose of improving the resilience of urban logistics is to enable the urban logistics system to respond and recover quickly when facing disturbances or shocks, and to maintain a relatively stable logistics service supply capacity. The resilience of urban logistics system is affected by many factors such as the development level of urban logistics, urban economic environment, logistics industrial structure, urban infrastructure, innovation ability and government policies.

Quantitative analysis of urban logistics resilience

A. System function curve

Before the quantitative analysis of urban logistics resilience, the concept of "system function curve" is introduced. System function curve, which is a continuous segmental function, is often used in the simulation of urban safety resilience, and is used to describe the function change process of the system when it is subjected to external impact. As shown in

Figure 1, time is usually represented by the horizontal axis, the vertical axis represents the system function, and the area enclosed by the curve and the horizontal axis represents the system function in a period of time. The system function curve reflects the process of the system function fluctuation with time after disturbance or impact. The resistance and recovery of the system to shocks can be improved by pre-prevention, in-process response and post-recovery.

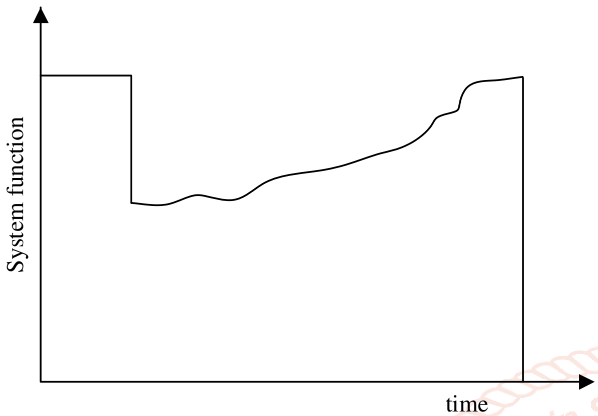


Figure 1 System function curve (adapted from Bruneau, 2003)

B. Function curve of urban logistics system

Based on the concept of system function curve, when characterizing the resilience of urban logistics system, the function curve of urban logistics system can be constructed by using the horizontal axis to represent time and the vertical axis to represent the function of urban logistics system. The function of urban logistics system refers to the logistics service capability that urban logistics system can provide, as shown in Figure 2.

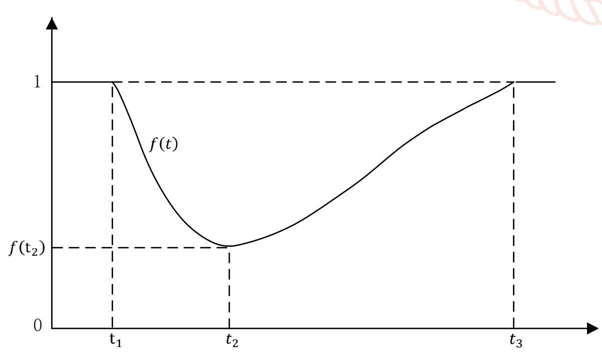


Figure 2 Schematic diagram of the function curve of urban logistics system

In Figure 2: t_1 to t_3 represent a complete cycle of resistance, adjustment and recovery of the urban logistics system after it suffers from a disturbance or shock, and the duration of the cycle is represented by t_a, i.e., $t_a = t_3 - t_1$.

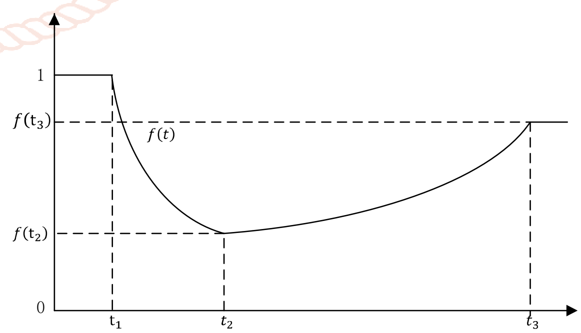
The system functioning can be represented by $f(t)$, where before the perturbation or shock, i.e. when $t < t_1$, the logistics system functioning is at the normal level and assuming $f(t) = 1$.

At the moment of t_1, the urban logistics system starts to suffer from disturbance or impact, and the function of the logistics system declines until the moment of t_2, when it falls to the lowest point, $0 \leq f(t_2) \leq 1$. With the implementation of the corresponding restoration measures, the function of the logistics system gradually recovers, and at the moment of t_3, it recovers to the original logistics service level or the target logistics service level, and maintains the stability for a period of time.

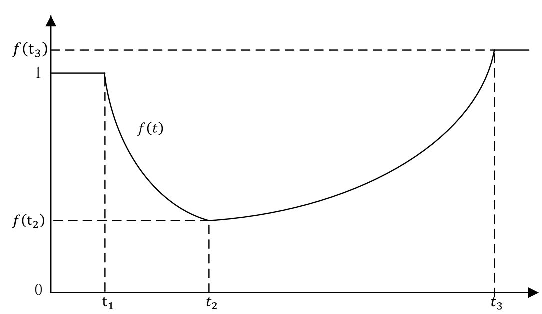
Wherein, the phase from t_1 to t_2 can be expressed as the resistance phase of the urban logistics system after it suffers a perturbation or shock, and the duration of this phase is $t_d = t_2 - t_1$, and the lost function of the system can be expressed by $f(t_1) - f(t_2)$, and the degree of resistance is expressed by k_d.

The phase from t_2 to t_3 represents the recovery adaptation stage of the urban logistics system after it suffers from perturbation or shock, and the duration of this stage is $t_h = t_3 - t_2$, the function of system recovery can be expressed by $f(t_3) - f(t_2)$, and the recovery rate is expressed by k_h.

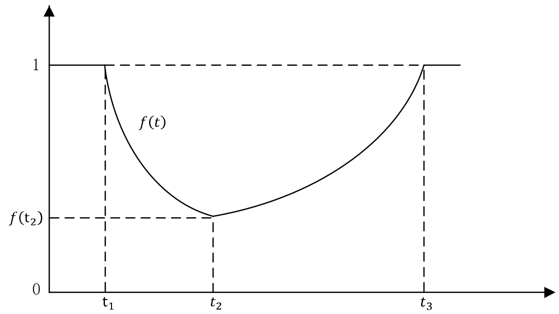
In order to further describe the system function manifestations of different logistics systems after impact, based on the concept of urban logistics system function curve, the functional recovery of urban logistics systems under several different circumstances is listed, as shown in Figure 3.



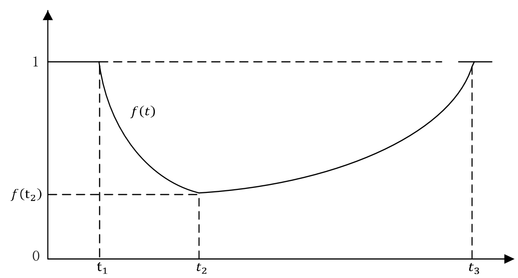
(a)



(b)



(c)



(d)

Figure 3 Function comparison of logistics systems in different cities

If the resistance and adaptability of the urban logistics system is poor, the emergency response is slow and the recovery ability is insufficient, then the function level of the urban logistics system suffers from the impact of a larger decline, and the resistance, adjustment and recovery cycle t_a lasts for a longer period of time, and it is difficult to recover to the original level of function even with a given amount of restoration of manpower and material inputs, as shown in Figure 3 (a).

If the resistance capacity of the urban logistics system is poor, but the adaptability and recovery ability are good, the rescue response after the event is sufficient and timely, and the urban logistics system has a good improvement ability, the system function level may be further improved on the basis of restoring the original function level, as shown in Figure 3 (b).

If the urban logistics system itself has poor resistance, adaptation and recovery ability, and its function level decreases greatly after the impact, but after the disturbance and impact, the government or the superior government and relevant social organizations actively participate in the rescue and invest a lot of human, material and financial resources, the time for the urban logistics system to recover to the original function level is shorter, as shown in Figure 3 (c).

If the urban logistics system is slow to recover after disturbance and impact, although it can finally recover to the original system function level, the recovery process lasts a long time, and the logistics service capability provided by the system is also low, as shown in Figure 3 (d).

C. Quantifying the resilience of urban logistics systems based on function curves

With the help of the functional curve of urban logistics system, when characterizing the resilience of urban logistics system, the degree of functional decline, recovery degree and recovery time of urban logistics system after impact can be used as indicators to quantify urban logistics resilience R, that is, the resilience level R of urban logistics system can be expressed as:

$$R = \frac{\int_{t_1}^{t_2} f(t)\,dt + \int_{t_2}^{t_3} f(t)\,dt}{\int_{t_1}^{t_3} 1\,dt} \tag{1}$$

$$k_d = \frac{\partial f(t)}{\partial t}, t \in [t_1, t_2] \tag{2}$$

$$k_h = \frac{\partial f(t)}{\partial t}, t \in [t_2, t_3] \tag{3}$$

In the above formula: $t_1 \le t_2 \le t_3$, $R \in [0,1]$, $f(t) \in [0,1]$。

Combined with Fig. 2 and equations (1), (2), and (3), it can be seen that the smaller the functional loss of the urban logistics system after disturbance or shock, the shorter the time t_h take in the resistance and recovery phase. The larger the value of the k_d and the smaller the value of the k_h, the stronger the resistance and resilience of the urban logistics system, the greater its resilience value R, and the stronger the resilience of the urban logistics system.

In the process of quantitative analysis of the resilience of urban logistics systems, it is necessary to characterize the functioning of urban logistics systems. The main factors affecting the functioning of urban logistics systems include external shocks, subsystem functioning and recovery measures. In this paper, we mainly consider subsystem function, external shocks and recovery measures to construct a quantitative analysis framework of urban logistics system function.

In terms of subsystem function, the urban logistics system consists of several interconnected subsystems, so its system function can be expressed by the sum of the functions of each subsystem:

$$f(t) = \sum f_i(t) \tag{4}$$

In Eq. (4), $f(t)$ is the function of urban logistics system, and $f_i(t)$ is the function of each subsystem of urban logistics system.

In terms of external shocks, the function that defines the decline in the functioning of the city's logistics system at the moment t due to the unexpected event e is $s(t|e)$,and by equation (4), the city's logistics system consists of various sub-systems, and therefore there are:

$$s(t|e) = \sum s_i(t|e) \quad (5)$$

In Eq. (5): $s_i(t|e)$ is a function of the degradation of the functioning of the logistics subsystem of the city at the moment $t$due to the unexpected event e.

In addition, logistics as a kind of derived demand, in analyzing the impact on the urban logistics system, it is not only necessary to consider the decline in function caused by external factors on the impact on the logistics system, such as the paralysis of traffic caused by the destruction of roads, the lack of capacity caused by the destruction of transport vehicles, and the poor turnover of materials caused by the destruction of warehousing facilities, and so on. It is also necessary to consider the changes in the city's demand for logistics after the impact, such as natural disasters type of emergencies after the protection and supply of urban residents' necessities of life materials on the logistics demand; public health emergencies, due to the emergency caused by the panic of the residents, which may lead to a short period of time, such as a sudden increase in the demand for logistics. Therefore, the incremental function of logistics demand in the city at the moment t after an emergency event e is defined as $d(t|e)$.

In terms of recovery measures, the function that defines the various measures taken by the city to recover the functioning of the urban logistics system after an emergency is $h(t|e)$, which similarly has:

$$h(t|e) = \sum h_i(t|e) \quad (6)$$

In Eq. (6): $h_i(t|e)$ is the function of the recovery of logistics subsystem function of the city at the moment t due to the unexpected event e. Therefore, the change function of logistics system function in the city at moment t due to unexpected event e can be expressed as:

$$f(t|e) = \sum f_i(t|e) - \sum s_i(t|e) + \sum h_i(t|e) - d(t|e) \quad (7)$$

The above discussion involves the three aspects of urban subsystems, external shocks and resilience, thus constituting an analytical framework for the functioning of the urban logistics system, and the model can be further defined, unfolded and expanded according to the problems in the specific analysis.

Conclusion

This paper explains the connotation of urban logistics system toughness, analyzes the resistance, adaptability and resilience of urban logistics system toughness; combines the function curve with the urban logistics system, characterizes the function of the urban logistics system and its functional changes after the impacts based on the function curve; compares the recovery of function curves of different logistics systems; constructs a model for the assessment of the toughness of the urban logistics system; and makes a preliminary exploration of the representation of the function of the urban logistics system. A model of urban logistics system resilience assessment was constructed, and a preliminary exploration of the representation of urban logistics system functions was carried out.

It should be pointed out that the innovation of using the toughness theory to introduce the concept of function curve to study the urban logistics system comes from the perspective of looking at the problem and the methodology used, and there is still a lot of room for improvement in urban logistics toughness as an emerging theoretical paradigm, and the significance of the theoretical changes and paradigm transformation that it brings is indisputable, and the significance of its significance in practice is also expected by the government and the society, so the research and exploration of this topic has a great importance. The research and discussion of this topic has a very urgent theoretical and practical needs, related issues such as quantitative research on toughness, but also to carry out more in-depth exploration and research.

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