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Research on the urban resilience evaluation with hybrid multiple attribute TOPSIS method: an example in China

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Abstract
Cities are important barriers to protect people's lives and property in the face of natural disasters, economic fluctuations and epidemic diseases. The evaluation of urban resilience is a hybrid multiple attribute group decision-making problem involving both crisp and fuzzy indicators. In order to evaluate the urban resilience reasonably and quantitatively, an urban resilience evaluation index system is established, including four primary indicators of ecological environment, municipal facilities, economic development and social development, and 28 secondary indicators. An evaluation model based on the theory of intuitionistic fuzzy set and TOPSIS method is proposed. The intuitionistic trapezoidal fuzzy number is used to quantify the fuzzy index and determine the weights of experts. The weight of each index is determined based on the maximizing deviation method. The relevant data of Dalian City from 2013 to 2017 are collected to evaluate the city resilience, and a sensitivity analysis is carried out based on the proposed model. The results may provide insights for the further urban resilience promotion.

Keywords Urban resilience · Hybrid multiple attribute group decision-making · TOPSIS method · Intuitionistic trapezoidal fuzzy numbers

1 Introduction

Nowadays, the impacts of extreme weather and natural disasters are getting increasingly severe. According to the data of China Statistical Yearbook, dozens of hazards occur every year, causing direct economic losses amount to tens of billions Yuan. Cities need not only to establish a defense system against natural disasters, but also to protect the lives and properties of residents from hazards such as economic fluctuations and epidemics (Godschalk 2003). Therefore, cities need an ability to defend, recover and adapt disturbances when facing with them (Fang et al. 2017; Chen et al. 2018). Evaluating urban resilience and analyzing the factors that influence city's response to hazards can

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find weak points in urban management, so that relevant departments can take targeted improvement measures and build a stronger city.

In recent years, there have been more and more studies on resilience evaluation (Cutter et al. 2008; Leichenko 2011; Cavallaro et al. 2014; Meerow et al. 2016; Wu et al. 2016). Martins et al. (2012) used GIS and multi-criteria analysis to evaluate social resilience facing with seismic risk in three disaggregation levels. Dong et al. (2017) studied the resilience of urban drainage systems, considering the severity of floods, climate change and urbanization. Donovan and Work (2017) quantitatively measured the resilience of transportation systems using GPS data of nearly 700 million taxi trips during Hurricane Sandy. Wang et al. (2018) discussed the urban resilience of Beijing from 1978 to 2015 from a comprehensive perspective of the social–economic–ecological system. Cui and Li (2020) used the social network analysis (SNA) method to measure the community's resilience from the perspective of social capital of stakeholders.

Based on the previous studies of recent years, when evaluating resilience, the subjects of scholars' research covered different levels such as communities, cities and regions (Cutter et al. 2014; Qasim et al. 2016; Zhang et al. 2017). The research methods involved mathematical analysis methods and spatial analysis methods (Cimellaro et al. 2010; Chen et al. 2018; Wang et al. 2018). Moreover, most scholars focused on the performance of cities in response to a single disaster such as earthquake or flood disasters (Martins et al. 2012; Lyu et al. 2018), while the engagement with the evaluation of comprehensive urban resilience is still limited. Additionally, when evaluating the urban resilience comprehensively, it is necessary to consider the impact of various factors such as social, economic and environmental factors (Wang et al. 2018). The evaluation indicators have characteristics of both accuracy and fuzziness, and some indicators need to be quantified by the subjective opinions of experts. Therefore, the comprehensive urban resilience evaluation is a hybrid multiple attribute group decision-making problem, but the research of scholars on solving this problem is still limited. In order to bridge the gap, the specific objective of this study was to propose a method in solving the hybrid multi-attribute urban resilience evaluation problem and evaluate the comprehensive urban resilience of a certain city, hoping it may help to improve the city resilience.

TOPSIS is a simple and practical approach for multi-criteria decision-making (MCDM) problems proposed by Hwang et al. (1993). The optimal solution is found by evaluating the distance between the feasible solution and the positive and negative ideal solutions. In the past few decades, scholars have expanded the use of TOPSIS method in various fuzzy environments and proposed methods such as ordinary fuzzy TOPSIS, interval-valued TOPSIS, IF-TOPSIS and hesitant fuzzy TOPSIS (Gündoğdu and Kahraman 2019). These years, fuzzy TOPSIS methods have been widely used in many fields such as engineering (Yazdi 2018), computer science (Beskese et al. 2015), business management (Yazdani et al. 2019) and environmental science (Guo and Zhao 2015). Therefore, a fuzzy approach can be used to deal with these types of circumstances.

Intuitionistic fuzzy set (IFS) is an extension of traditional fuzzy set proposed by Atanassov (1986), which includes the membership and non-membership functions and hesitation margin groups. In the group decision-making process, different backgrounds, personal habits, the nature of human judgment or vague knowledge about the preference degree of experts will lead to different evaluation results (Liao et al. 2014; Wang et al. 2016). Intuitive trapezoidal fuzzy numbers can not only express decision makers' uncertainty and hesitation when considering the membership of indicators, but also express decision information in different dimensions (Li and Chen 2014; Wei 2015).

Thus, combining the intuitionistic fuzzy set with the traditional TOPSIS method can well solve the hybrid multi-attribute urban resilience evaluation problem.

As discussed earlier, the main objective of this study was to provide an appropriate comprehensive urban resilience evaluation method under hybrid multiple attribute environment. The remainder of this paper is organized as follows: In Sect. 2, a comprehensive urban resilience evaluation index system is established. In Sect. 3, a comprehensive urban resilience evaluation model based on intuitionistic trapezoidal fuzzy numbers and TOPSIS method is proposed. The fourth part presented an empirical study based on data of Dalian, China in 2013–2017. The results are discussed in Sect. 5, and a sensitivity analysis based on the model is carried out. Finally, the conclusions and future works are described in the last section.

2 The establishment of urban resilience evaluation index system

“City” is a geographical term, divided by administrative jurisdiction. In 2019, China’s urbanization rate exceeded 60%. China is in the stage of rapid urbanization, and the urban population and wealth have increased dramatically (Fang et al. 2017). Cities are not only a carrier of production and residents’ life, but also an important protector against hazards (Godschalk 2003; Lhomme et al. 2013). A city can be regarded as an integrated system, consisting of many sub-systems such as building systems, medical systems, transportation systems and government management systems (Javidroozi et al. 2015). The effective operation and cooperative work of these systems ensure the normal function of a city. The term “resilience” originated in ecology, it is considered that the resilience of an ecosystem can maintain normal operation when exposed to external threats, or it can return to equilibrium after being disturbed (Hoiling 1973; Folke 2006). These years, scholars extended the definition of resilience and combined it with urbanism and proposed the concept of “urban resilience” (Cavallaro et al. 2014; Meerow et al. 2016; Chen et al. 2018).

Scholars’ explanation of resilience varies (Ahern 2011; Lhomme et al. 2013; Lu and Stead 2013; Bozza et al. 2015). Generally, urban resilience can be summarized to the following three aspects of the ability of urban integrated system: firstly, the ability of a city to maintain normal functions without external help when it is exposed to an emergency (such as an earthquakes, floods, or epidemics); secondly, the ability of a city to back to normal in time when the urban sub-systems are interfered; and thirdly, the ability of a city to adjust and adapt to the experiences and ready to meet future challenges (Fang et al. 2017).

With reference to the relevant literature, it is difficult to accurately orient certain indicators of the city to one of the above three abilities. With consideration of the three abilities above, many organizations and scholars have proposed frameworks regarding city as a system to evaluate the urban resilience. The United States Agency for International Development, the World Bank and the Rockefeller Foundation has all proposed frameworks to evaluate urban resilience (UNISDR 2005; McAllister 2015). The UK government proposed the *Strategic National Framework on Community Resilience* in 2011 to develop key resilience factors for community resilience (Cabinet Office of UK 2011). Researchers from Kyoto University and Kitakyushu City Center in Japan have also established a comprehensive evaluation framework of resilient cities system (GFDRR 2016). Usually, the evaluation system of urban resilience involved aspects of social, economic, institutional and physical; some of the researchers divided it more detailed into biodiversity, modularity, tight feedbacks, social capital, acknowledging slow variables and thresholds, and innovation (Walker and Salt 2006; Cutter et al. 2008; Orencio and Fujii 2013; Singh-Peterson et al. 2014; Qasim et al. 2016).

Based on the previous studies combined with China's national conditions and taking data availability into account, we established an urban resilience evaluation index system as shown in Table 1. The indicators of the system covered four first-level aspects of ecological environment, public infrastructure, economic development and social development, and 28 second level indicators (the first 5 indicators under each first level can be quantified by crisp numbers, and the others are fuzzy numbers). Divided from most of the studies, this evaluation system put natural disaster risk and climate change risk into consideration, in order to provide an indicator for following analysis of concerns (refer to Sect. 5).

3 Methodologies

3.1 Intuitionistic trapezoidal fuzzy numbers

Let A be an intuitionistic trapezoidal fuzzy number on the set of real numbers, $A=\langle(a_1, a_2, a_3, a_4), (a_5, a_6, a_7, a_8)\rangle$, where $a_5 \le a_1 \le a_6 \le a_2 \le a_3 \le a_7 \le a_4 \le a_8$, then the membership function and non-membership function of intuitionistic trapezoidal fuzzy number A can be defined as follows:

$$\mu_A(x) = \begin{cases} \frac{x-a_1}{a_2-a_1}, & a_1 \le x \le a_2 \\ 1, & a_2 \le x \le a_3 \\ \frac{x-a_3}{a_4-a_3}, & a_3 \le x \le a_4 \\ 0, & \text{else} \end{cases} \qquad \nu_A(x) = \begin{cases} \frac{x-a_5}{a_6-a_5}, & a_5 \le x \le a_6 \\ 1, & a_6 \le x \le a_7 \\ \frac{x-a_7}{a_8-a_7}, & a_7 \le x \le a_8 \\ 0, & \text{else} \end{cases} \tag{1}$$

As for fuzzy number $\tilde{a}=\langle(4, 6, 7, 8), (4, 5, 7, 9)\rangle$, when $x=5$, the degree of membership $\mu_{\tilde{a}}$ of fuzzy number $\tilde{a}$ is 0.5, the non-membership is 0, and $\pi_{\tilde{a}} = 1 - \mu_{\tilde{a}} - \nu_{\tilde{a}} = 0.5$ denotes the hesitation of fuzzy number, representing the hesitation of decision makers when considering the degree of membership.

Let A and B be two intuitionistic trapezoidal fuzzy numbers, $A=\langle(a_1, a_2, a_3, a_4), (a_5, a_6, a_7, a_8)\rangle$, $B=\langle(b_1, b_2, b_3, b_4), (b_5, b_6, b_7, b_8)\rangle$, then the distance between them can be calculated as follows (Chen and Li 2013):

$$\begin{aligned} D(A,B) = \Bigg(\frac{1}{12}\Bigg(&\sum_{i=1}^{8}(b_i - a_i)^2 + (b_8 - a_8)(b_7 - a_7) + (b_6 - a_6)(b_5 - a_5) \\ &+(b_4 - a_4)(b_3 - a_3) + (b_2 - a_2)(b_1 - a_1)\Bigg)\Bigg)^{\frac{1}{2}} \end{aligned} \tag{2}$$

The crisp number is a special case of the fuzzy number, when A and B are both crisp numbers, there is $a_1=\cdots=a_8=a$, $b_1=\cdots=b_8=b$, and Eq. (2) can be simplified to:

$$D(A,B) = \sqrt{(b-a)^2} \tag{3}$$

3.2 Construct decision matrix

The evaluation of urban resilience with the coexistence of fuzzy number and crisp number is a mixed multi-attribute group decision-making problem. Let scheme set $Q=\{q_1, q_2, \ldots,$

Table 1 Urban Resilience Evaluation Index System

Primary Index	Secondary Index	The meaning of Indexes	Unit	Justification and effect on resilience
A Ecological environment	A_1	Regional environmental noise	dB	Improve living happiness and citizens will be more willing to cooperate in disasters; healthy cities have less chance of turbulence
	A_2	Waste water discharge	million tons	
	A_3	Exhaust emission (SO_2)	ten thousand tons	
	A_4	Number of waste water treatment facilities	set	Quickly treat sewage to prevent hazards from causing epidemics
	A_5	Number of waste gas treatment facilities	set	Ensured air quality and prevented respiratory diseases
	A_6	Natural disaster risk	null	Assess the level of disaster risk in cities; provide an indicator for the following analysis of concerns
	A_7	Climate change risk	null	
B Public facilities	B_1	Green area per capita	square meter	Good ecosystem has water holding and storage capacity
	B_2	Daily capacity of urban waste water treatment	million cubic meters	Represented the responding time of cities in the face of hazards
	B_3	Urban road area per capita	square meter	Urban roads can be used for evacuation and rescue
	B_4	Length of water supply pipeline	kilometer	Guaranteed basic supply in the event of hazards
	B_5	Length of artificial gas pipeline	kilometer	
	B_6	Government strategy and planning of further development	null	Government’s rapid response helps to deal quicker with hazards
	B_7	Construction of emergency communication services	null	Ensured communication and rescue in time

Table 1 (continued)

Primary Index	Secondary Index	The meaning of Indexes	Unit	Justification and effect on resilience
C Economic development	C_1	Gross domestic product per capita	yuan	Represented a city’s economic capacity
	C_2	Annual output value of tertiary industry	billion yuan	Tertiary industry drives economic growth and increases economic capacity
	C_3	Total export–import volume	ten thousand dollars	Improve trade structure and strengthen ability to resist financial crisis
	C_4	Actual utilization of foreign direct investment amount	ten thousand dollars	
	C_5	Deposit balance of financial institutions	ten thousand yuan	Government financial support is needed for city to recover from hazards
	C_6	Prices	null	Ensured the normal life of residents during hazards and stabilize popular feelings
	C_7	Economic innovation ability	null	Diversified income sources leads to fast recovery and rehabilitation
D Social development	D_1	Disposable personal income (DPI) of permanent residents	yuan	Ensured citizens to recover from hazards
	D_2	Number of health institutions	a	Ensured that injured people can be treated in time
	D_3	Number of participants in basic retirement security	ten thousand individuals	It helps vulnerable groups to recover from hazards
	D_4	Number of participants in unemployment insurance	ten thousand individuals	
	D_5	Number of Participants in basic medical insurance	ten thousand individuals	Ensured treatment and recovery in terms of injuries
	D_6	Poverty alleviation degree	null	People above poverty line may recover from hazards more quickly
	D_7	Social stability	null	When disasters occur, riots may happen

q_i, …, $q_m\}$ consists m schemes, each scheme set has n indexes, and the corresponding set of attributes is $P=\{p_1, p_2, \ldots, p_j, \ldots, p_n\}$. Let the attribute set of scheme i expressed as $S_i=\{s_{i1}, s_{i2}, \ldots, s_{ij}, \ldots, s_{in}\}$, among there are k crisp indicators and $n-k$ fuzzy indicators. Let $W=\{\omega_1, \omega_2, \ldots, \omega_j, \ldots, \omega_n\}$ be the weight set of indexes.

Experts usually use natural language to evaluate, and for calculation needs it should be quantified. The standard of transferring natural language into intuitionistic trapezoidal fuzzy numbers is shown in Table 2 (Chen and Li 2013). The decision matrix $S=(s_{ij})_{m\times(n-k)}$ is in the form of intuitionistic trapezoidal fuzzy numbers and comes from evaluating the $n-k$ fuzzy indicators of urban resilience in Table 1 by experts. The establishment of decision matrix $S=(s_{ij})_{m\times k}$ of crisp numbers is based on government open data.

3.3 Data standardization

In order to eliminate the influence of dimension and data size differences, it is necessary to standardize the decision matrix $S=(s_{ij})_{m\times(n-k)}$ and $S=(s_{ij})_{m\times k}$ we got. When the index value is crisp number, the normalized equation of income-type index is shown as follows:

$$x_{ij} = \frac{s_{ij}}{\sqrt{\sum_{i=1}^{m} (s_{ij})^2}}, \quad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n \tag{4}$$

The standardization equation of cost-type indicators is shown as follows:

$$x_{ij} = \frac{1/s_{ij}}{\sqrt{\sum_{i=1}^{m} (1/s_{ij})^2}}, \quad i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots \ldots, n \tag{5}$$

When the index value is an intuitionistic trapezoidal fuzzy number, the normalization equation of income-type index is shown as follows (Li and Chen 2014):

$$x_{ij} = \left\langle \begin{matrix} \left(\frac{s_{ij}^{(1)}}{\max\limits_i \{s_{ij}^{(1)}\}}, \frac{s_{ij}^{(2)}}{\max\limits_i \{s_{ij}^{(2)}\}}, \frac{s_{ij}^{(3)}}{\max\limits_i \{s_{ij}^{(3)}\}}, \frac{s_{ij}^{(4)}}{\max\limits_i \{s_{ij}^{(4)}\}} \right), \\ \left(\frac{s_{ij}^{(5)}}{\max\limits_i \{s_{ij}^{(5)}\}}, \frac{s_{ij}^{(6)}}{\max\limits_i \{s_{ij}^{(6)}\}}, \frac{s_{ij}^{(7)}}{\max\limits_i \{s_{ij}^{(7)}\}}, \frac{s_{ij}^{(8)}}{\max\limits_i \{s_{ij}^{(8)}\}} \right) \end{matrix} \right\rangle \tag{6}$$

The standardization equation of cost-type indicators is shown as follows:

Table 2 Transfer standard of natural language to intuitionistic trapezoidal fuzzy numbers

Natural language	Intuitionistic trapezoidal fuzzy numbers
Absolutely low	(0.0, 0.0, 0.0, 0.0), (0.0, 0.0, 0.0, 0.0)
Low	(0.0, 0.1, 0.2, 0.3), (0.0, 0.1, 0.2, 0.3)
Generally low	(0.1, 0.2, 0.3, 0.4), (0.0, 0.2, 0.3, 0.5)
Medium	(0.3, 0.4, 0.5, 0.6), (0.2, 0.4, 0.5, 0.7)
Generally high	(0.5, 0.6, 0.7, 0.8), (0.4, 0.6, 0.7, 0.9)
High	(0.7, 0.8, 0.9, 1.0), (0.7, 0.8, 0.9, 1.0)
Absolutely high	(1.0, 1.0, 1.0, 1.0), (1.0, 1.0, 1.0, 1.0)

$$x_{ij} = \left\langle \begin{array}{l} \left(\frac{\min\limits_i\{s_{ij}^{(1)}\}}{s_{ij}^{(1)}}, \frac{\min\limits_i\{s_{ij}^{(2)}\}}{s_{ij}^{(2)}}, \frac{\min\limits_i\{s_{ij}^{(3)}\}}{s_{ij}^{(3)}}, \frac{\min\limits_i\{s_{ij}^{(4)}\}}{s_{ij}^{(4)}} \right), \\ \left(\frac{\min\limits_i\{s_{ij}^{(5)}\}}{s_{ij}^{(5)}}, \frac{\min\limits_i\{s_{ij}^{(6)}\}}{s_{ij}^{(6)}}, \frac{\min\limits_i\{s_{ij}^{(7)}\}}{s_{ij}^{(7)}}, \frac{\min\limits_i\{s_{ij}^{(8)}\}}{s_{ij}^{(8)}} \right) \end{array} \right\rangle \tag{7}$$

The normalized matrix X is obtained after data standardization, the crisp number part is expressed as $X=(x_{ij})_{m\times k}$, and the fuzzy number part is expressed as $X=(x_{ij})_{m\times(n\text{-}k)}$.

3.4 Experts' weight determination

In the multi-attribute evaluation, a group of experts is required to participate in the evaluation in order to obtain reasonable results. Most of the time, expert weights are set equal in advance to simplify calculations (Chen 2000; Karsak and Dursun 2015; Wang et al. 2016). However, when evaluating the comprehensive urban resilience, the indicators involve information of four aspects: ecological environment, public facilities, economic development and social development. Due to the different knowledge background and experience of the experts, when evaluating indicators that are not from their familiar research areas, they are likely to give inappropriate values.

In the existing researches, the most commonly used method is to evaluate the expert weights subjectively such as AHP (Yue 2012; Liao et al. 2014; Yazdi 2018). However, there still exists uncertainty and it often causes excessive work. Therefore, a method proposed by Chen and Yang (2011) to calculate experts' weights objectively in the context of intuitionistic trapezoidal fuzzy numbers is used in this article.

Although the evaluation results of experts may vary greatly due to subjective consciousness, the experts invited for comprehensive city resilience assessment are not without such knowledge basic. Therefore, it is believed that the opinions of most experts in the evaluation process are correct, and few experts' view may be biased due to certain factors. Under such circumstances, Chen and Yang (2011) deduced that if the decision information of an expert is close to the mean value of group decision, the expert is given a larger weight; if the decision information of an expert deviates from the mean value of group decision, the expert is given a smaller weight.

Based on the above concepts, as for the index x_{ij} in the normalized matrix X, the weight ξ_{ij}^h of expert h can be calculated as follows:

$$\xi_{ij}^h = \left(1 - \frac{D(x_{ij}^h, x_{ij}^H)}{\sum_{h=1}^l D(x_{ij}^h, x_{ij}^H)}\right) \Bigg/ \left(\sum_{h=1}^{l} \left(1 - \frac{D(x_{ij}^h, x_{ij}^H)}{\sum_{h=1}^l D(x_{ij}^h, x_{ij}^H)}\right)\right) \tag{8}$$

Among them, x_{ij}^h represents the evaluation value of the index p_j in scheme q_i, given by expert h. x_{ij}^H represents the mean value of group decision of the index p_j in scheme q_i, $x_{ij}^H = \frac{1}{l}\sum_{h=1}^{l} x_{ij}^l$. $D(x_{ij}^h, x_{ij}^H)$ represents the distance between the evaluation value of expert h and the mean value of group decision; it can be calculated based on Eq. (2).

3.5 Index weight determination

Maximizing deviation method is used to calculate index weights in this article (Wei 2015). The basic concept of calculating index weights by this method is as follows: As for single attribute p_j, the greater the differences of attribute values x_{ij} among the m schemes, the bigger the effect of this attribute have during decision-making, thus greater weight value should be assigned. Relatively, the smaller the difference, the smaller the role of the attribute plays in decision-making, and the smaller the weight value should be given.

Based on the above concepts, in the normalized decision matrix X, for indicator p_j, the difference between the attribute values x_{ij} of the scheme q_i and those of other attributes can be defined as $d_{ij}(\omega_j) = \sum_{k=1}^{m} d(x_{ij}, x_{kj})\omega_j$; thus, for indicator p_j, the total deviation of all of the schemes can be defined as $d_j(\omega) = \sum_{i=1}^{m} d_{ij}(\omega) = \sum_{i=1}^{m} \sum_{k=1}^{m} d(x_{ij}, x_{kj})\omega_j$. The selection of index weight should maximize the total deviation of all indicators from all schemes.

Therefore, a linear programming model (9) is established to solve the single objective optimization problem as follows:

$$\begin{cases} \max d(\omega) = \sum\limits_{i=1}^{m} \sum\limits_{j=1}^{n} \sum\limits_{k=1}^{m} d(x_{ij}, x_{kj})\omega_j \\ \text{s.t. } \sum\limits_{j=1}^{n} \omega_j^2 = 1, \quad \omega_j \geq 0, \quad j = 1, 2, \ldots, n \end{cases} \tag{9}$$

Construct Lagrange function:

$$L(\omega, \lambda) = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{m} d(x_{ij}, x_{kj})\omega_j + \lambda\left(\sum_{j=1}^{n} \omega_j^2 - 1\right) \tag{10}$$

s.t.

$$\frac{\partial L}{\partial \omega_j} = \sum_{i=1}^{m} \sum_{k=1}^{m} d(x_{ij}, x_{kj}) + 2\lambda\omega_i = 0 \tag{11}$$

$$\frac{\partial L}{\partial \lambda} = \sum_{j=1}^{n} \omega_j^2 - 1 = 0 \tag{12}$$

So we can get result as follows:

$$\omega_j = \frac{\sum_{i=1}^{m} \sum_{k=1}^{m} d(x_{ij}, x_{kj})}{\sqrt{\sum_{j=1}^{n} (\sum_{i=1}^{m} \sum_{k=1}^{m} d(x_{ij}, x_{kj}))^2}}, \quad j = 1, 2, \ldots, n \tag{13}$$

After normalization, the weight calculation equation is changed as follows:

$$\omega_j = \frac{\sum_{i=1}^{m} \sum_{k=1}^{m} d(x_{ij}, x_{kj})}{\sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{m} d(x_{ij}, x_{kj})}, \quad j = 1, 2, \ldots, n \tag{14}$$

3.6 The calculation of weighted normalization matrix

As for the normalization matrix $X = (x_{ij})_{m\times k}$ of crisp numbers, the weighted normalization matrix is defined as $R = (r_{ij})_{m\times k}$, where $r_{ij} = \omega_j \times x_{ij}$.

Similarly, as for the normalization matrix $X = (x_{ij})_{m\times(n-k)}$ of fuzzy numbers, the weighted normalization matrix is defined as $R = (r_{ij})_{m\times(n-k)}$, where $r_{ij} = \omega_j \times \sum_{h=1}^{l} \xi_{ij}^{h} x_{ij}^{h}$.

3.7 Ranking based on the IF-TOPSIS method

TOPSIS is a method to determine the optimal solution according to a limited number of target points, choosing the optimal solution by ranking the distances between the single target points and the optimal solution (Mohamed et al. 2019). IF-TOPSIS method which based on IFS and TOPSIS method is used in comprehensive urban resilience evaluation in this article (Büyüközkan and Güleryüz 2016; Zhang et al. 2019). If a certain target point is the nearest to the positive ideal solution and the farthest from the negative ideal solution, then the certain target point is the optimal solution.

As for attribute p_j of fuzzy number, define r_j^+ as the positive ideal solution and r_j^- as the negative ideal solution, then the equations for calculating the positive and negative ideal solutions of the indexes of fuzzy number are as follows:

$$r_j^+ = \langle (\max_i r_{ij}^{(1)}, \max_i r_{ij}^{(2)}, \max_i r_{ij}^{(3)}, \max_i r_{ij}^{(4)}), (\max_i r_{ij}^{(5)}, \max_i r_{ij}^{(6)}, \max_i r_{ij}^{(7)}, \max_i r_{ij}^{(8)}) \rangle \tag{15}$$

$$r_j^- = \langle (\min_i r_{ij}^{(1)}, \min_i r_{ij}^{(2)}, \min_i r_{ij}^{(3)}, \min_i r_{ij}^{(4)}), (\min_i r_{ij}^{(5)}, \min_i r_{ij}^{(6)}, \min_i r_{ij}^{(7)}, \min_i r_{ij}^{(8)}) \rangle \tag{16}$$

As for the attributes of crisp number, the equations for calculating positive and negative ideal solutions are as follows:

$$r_j^+ = \max_i r_{ij}, \quad r_j^- = \min_i r_{ij} \tag{17}$$

Therefore, based on Eqs. (2) and (3), the distance between the scheme q_i and the positive and negative ideal solutions are as follows:

$$d_i^+ = \sqrt{\sum_{j=1}^{k} (r_{ij} - r_j^+)^2 + \sum_{j=k+1}^{n} D(r_{ij}, r_j^+)}, \quad d_i^- = \sqrt{\sum_{j=1}^{k} (r_{ij} - r_j^-)^2 + \sum_{j=k+1}^{n} D(r_{ij}, r_j^-)} \tag{18}$$

The equation for calculating the comprehensive closeness of each scheme is as follows:

$$C_i^* = d_i^- / (d_i^+ + d_i^-) \tag{19}$$

Then, the urban resilience can be evaluated by comparing the values of comprehensive closeness.

4 Case study

4.1 Basic information and data collection

Dalian is located at the southern end of the Liaodong Peninsula in China, located between 38°43′ and 40°12′ North latitude and 120° 58′ and 123° 31′ East longitude. As a coastal city, it has a large port and is connected to a vast hinterland, so it is the hub of sea and land transportation. Moreover, it is also a connection point for economic, cultural and technical exchanges at home and abroad.

The data of Dalian City (China) from 2013 to 2017 are selected to analyze the changes of urban resilience, expecting to provide guidance for the next few years' urban construction of relevant government departments. The data are from Liaoning Province Statistical

Yearbook (http://www.ln.stats.gov.cn/tjsj/sjcx/ndsj/), Dalian National Economic and Social Development Statistical Bulletin (http://www.stats.dl.gov.cn/index.php?m=content&c=index&a=lists&catid=52) and Dalian Environmental Status Bulletin (http://www.epb.dl.gov.cn/common/list.aspx?mid=328). The original data are shown in Appendix, and the decision matrix $S=(s_{ij})_{5\times 20}$ of crisp number is obtained based on it.

Four experts are invited to make evaluation for eight fuzzy indexes (A_6, A_7, B_6, B_7, C_6, C_7, D_6, D_7) from 2013 to 2017, and decision matrix $S=(s_{ij})_{5\times 8}$ of fuzzy number is obtained based on the transfer standard of natural language to intuitionistic trapezoidal fuzzy numbers in Table 2.

4.2 Urban resilience evaluation

First of all, the original data should be standardized based on Eqs. (4)–(7). In this example, 6 out of the 28 indexes are cost-based indicators (A_1, A_2, A_3, A_6, A_7, C_6), the smaller the better. The other 22 indexes are income-based indicators, the bigger the better. By normalizing the data in the matrix S, we can obtain two normalization matrices: the normalization matrix $X=(x_{ij})_{5\times 20}$ of crisp number and the normalization matrix $X^{(h)}=(x_{ij}^{(h)})_{5\times 8}$ $(h=1,2,3,4)$ of fuzzy number evaluated by 4 experts.

Subsequently, based on the results of the fuzzy number normalization matrix, calculate the weights of 4 experts according to Eqs. (2) and (8). The weight results are shown in Table 3.

Then, according to the maximizing deviation method, the weight of each indicator can be obtained. When calculating weights, there are 20 crisp indicators and 8 fuzzy ones. We can get from Eq. (14) that the key to carrying out indicator weights is to calculate the distance (difference) between an indicator of a single year and the others. The distance between the crisp indicators is determined by the data in the statistical yearbook and calculated according to Eq. (3); the distance between the fuzzy indicators is calculated by the expert's fuzzy value and corrected based on the expert weight in Table 3 and then calculated according to Eq. (2). Furthermore, the weight of each indicator can be obtained according to Eq. (14). The weights of the 28 indicators are shown in Table 4.

Additionally, we aggregate the weights of normalized matrix X, and the weighted normalized matrix $R=(r_{ij})_{5\times 20}$ of crisp number and the weighted normalized matrix $R=(r_{ij})_{5\times 8}$ of fuzzy number are obtained. The weighted normalized matrix $R=(r_{ij})_{5\times 8}$ of fuzzy number is shown in Table 5. Because the matrix is too large, only R_{i6} and R_{i7} are shown in this article. The weighted normalized matrix $R=(r_{ij})_{5\times 20}$ of crisp number is shown in Table 6.

5 Results and discussions

Based on Eqs. (15)–(19), TOPSIS method is used to determine the distances between single schemes and the positive and negative ideal solutions, and the comprehensive closeness of the schemes is obtained as shown in Table 7.

By comparing the comprehensive closeness value in Table 7, we can draw a conclusion that the urban resilience of Dalian city from 2013 to 2017 is $2017>2016>2015>2013>2014$.

In the past 5 years (2013–2017), the Dalian Municipal Government has invested a lot of manpower, material resources and financial resources to improve the comprehensive

Table 3 Weights of 4 experts ($\xi_{ij}^{(h)}$ $(h = 1, 2, 3, 4)$)

	A_6	A_7	B_6	B_7	C_6	C_7	D_6	D_7
2013								
Expert 1	0.250	0.250	0.250	0.306	0.250	0.250	0.083	0.250
Expert 2	0.250	0.250	0.250	0.306	0.250	0.250	0.306	0.250
Expert 3	0.250	0.250	0.250	0.083	0.250	0.250	0.306	0.250
Expert 4	0.250	0.250	0.250	0.306	0.250	0.250	0.306	0.250
2014								
Expert 1	0.306	0.306	0.250	0.083	0.306	0.250	0.250	0.083
Expert 2	0.306	0.306	0.250	0.306	0.083	0.250	0.250	0.306
Expert 3	0.083	0.306	0.250	0.306	0.306	0.250	0.250	0.306
Expert 4	0.306	0.083	0.250	0.306	0.306	0.250	0.250	0.306
2015								
Expert 1	0.328	0.250	0.306	0.306	0.250	0.250	0.306	0.306
Expert 2	0.123	0.250	0.306	0.306	0.250	0.250	0.306	0.306
Expert 3	0.328	0.250	0.306	0.306	0.250	0.250	0.306	0.083
Expert 4	0.220	0.250	0.083	0.083	0.250	0.250	0.083	0.306
2016								
Expert 1	0.257	0.306	0.169	0.250	0.250	0.250	0.306	0.083
Expert 2	0.306	0.306	0.333	0.250	0.250	0.250	0.306	0.306
Expert 3	0.180	0.083	0.165	0.250	0.250	0.250	0.306	0.306
Expert 4	0.257	0.306	0.333	0.250	0.250	0.250	0.083	0.306
2017								
Expert 1	0.328	0.250	0.083	0.250	0.083	0.250	0.083	0.250
Expert 2	0.220	0.250	0.306	0.250	0.306	0.250	0.306	0.250
Expert 3	0.123	0.250	0.306	0.250	0.306	0.250	0.306	0.250
Expert 4	0.328	0.250	0.306	0.250	0.306	0.250	0.306	0.250

Table 4 Weight of each index (ω_{ij})

	A-level index	*B*-level index	*C*-level index	*D*-level index
1	0.0028	0.0203	0.0239	0.0597
2	0.0330	0.0674	0.0489	0.0167
3	0.1135	0.0110	0.0418	0.0297
4	0.0622	0.0281	0.0571	0.0137
5	0.0742	0.0152	0.0571	0.0206
6	0.0179	0.0273	0.0296	0.0249
7	0.0357	0.0231	0.0220	0.0224

economic strength, environmental quality and people's living standards. According to the three capabilities required for urban resilience mentioned in Sect. 2, the results are discussed below.

Table 5 Weighted normalized matrix of fuzzy number $(R=(r_{ij})_{5\times8})$

	A_6	A_7
2013	(0.018, 0.018, 0.018, 0.018), (0.000, 0.018, 0.018, 0.018)	(0.036, 0.036, 0.036, 0.036), (0.036, 0.036, 0.036, 0.036)
2014	(0.008, 0.012, 0.014, 0.015), (0.000, 0.012, 0.014, 0.014)	(0.023, 0.026, 0.028, 0.029), (0.016, 0.026, 0.028, 0.030)
2015	(0.009, 0.013, 0.015, 0.016), (0.000, 0.013, 0.015, 0.015)	(0.018, 0.021, 0.024, 0.026), (0.012, 0.021, 0.024, 0.027)
2016	(0.005, 0.009, 0.012, 0.013), (0.000, 0.009, 0.012, 0.013)	(0.015, 0.018, 0.021, 0.023), (0.009, 0.018, 0.021, 0.024)
2017	(0.009, 0.013, 0.015, 0.016), (0.000, 0.013, 0.015, 0.015)	(0.014, 0.018, 0.020, 0.022), (0.009, 0.018, 0.020, 0.024)

Table 6 Weighted normalized matrix of crisp number $(R=(r_{ij})_{5\times20})$

	2013	2014	2015	2016	2017
A_1	0.0013	0.0013	0.0013	0.0013	0.0013
A_2	0.0136	0.0138	0.0150	0.0152	0.0162
A_3	0.0384	0.0413	0.0408	0.0578	0.0686
A_4	0.0305	0.0311	0.0282	0.0270	0.0212
A_5	0.0317	0.0317	0.0357	0.0397	0.0252
B_1	0.0097	0.0089	0.0093	0.0088	0.0087
B_2	0.0255	0.0268	0.0295	0.0298	0.0376
B_3	0.0049	0.0048	0.0048	0.0049	0.0051
B_4	0.0119	0.0121	0.0122	0.0124	0.0141
B_5	0.0065	0.0066	0.0068	0.0069	0.0071
C_1	0.0103	0.0111	0.0110	0.0111	0.0098
C_2	0.0185	0.0208	0.0223	0.0250	0.0222
C_3	0.0180	0.0192	0.0214	0.0179	0.0168
C_4	0.0222	0.0229	0.0247	0.0274	0.0297
C_5	0.0215	0.0239	0.0243	0.0277	0.0294
D_1	0.0221	0.0243	0.0270	0.0288	0.0306
D_2	0.0073	0.0072	0.0073	0.0077	0.0079
D_3	0.0119	0.0130	0.0134	0.0137	0.0142
D_4	0.0058	0.0061	0.0062	0.0063	0.0063
D_5	0.0085	0.0091	0.0094	0.0095	0.0095

Table 7 Distance measures and comprehensive closeness

	d_i^+	d_i^-	C_i^*
2013	0.00125	0.00043	0.25665
2014	0.00086	0.00029	0.25298
2015	0.00088	0.00033	0.27462
2016	0.00032	0.00068	0.68280
2017	0.00044	0.00137	0.75669

5.1 Ability of defend

The construction of defensive infrastructure can withstand disasters, and the construction of urban roads is conducive to evacuation and rescue. By comparing the original data of 2013 and 2014, we can see that the per capita urban road area in 2013 is larger than that in 2014, which leads to a slightly better urban resilience result in 2013 than in 2014. The decrease in per capita urban road area is related to the urban construction of Dalian municipal government and the annual growth of population. After 2014, the per capita urban road area has increased slightly, and the number of health institutions has also increased. This indicates that in recent years, Dalian municipal government has increased investment in public facilities and infrastructure construction.

5.2 Ability of recover

The level of economic development is critical to the city's ability to recover from disasters. Individual disposable balances and government financial savings can also help. SINOCHEMICAL GROUP has settled in Dalian for years, which has promoted the development of Dalian's economy and made Dalian one of the most important oil refining bases in China. The increase in total imports and exports and foreign investment has also promoted Dalian's economic growth.

5.3 Ability of adapt

Investment for environmental protection can not only improve the city's ability to adapt to disasters, but also improve the happiness of residents' lives, which is conducive to social stability. In 2016 and 2017, urban resilience has been significantly improved compared with the previous 3 years. The main reason is the development of air pollution control project. In 2016, sulfur dioxide emission reduction reached 29.44%, and the government promoted 146 gas emission reduction projects.

5.4 Sensitivity analysis

We performed a quantitative analysis based on the model proposed for further study. Monte Carlo Simulation (Simanaviciene and Ustinovichius 2010; Dutta et al. 2019) is a quantitative method to test the impact of uncertain inputs on results. In this paper, we used this method to study the changing impact of 28 indicators on the final result. Meanwhile, we hoped that the study may then promote further insights of the factors which affect urban resilience most.

Oracle Crystal Ball is an open-source plug-in software of Microsoft Excel, which can analyze the uncertainties through Monte Carlo simulation. Because it requires less user intervention and has a powerful probability distribution library, it is widely used for sensitivity analysis in many fields such as project management, financial analysis and risk management (Bieda 2013; Mantzaras and Voudrias 2017). We used this software carried out 10,000 time's Monte Carlo simulations and set a confidence rate of 95%. Subsequently, the variance contribution of the 28 indicators in the comprehensive evaluation of urban resilience from 2013 to 2017 is shown in Table 8, and the corresponding chart is made using Origin 2018 (Fig. 1).

As can be seen from Fig. 1, we can carry out a conclusion that the top five sensitive factors of urban resilience from 2013 to 2017 are A_7, A_3, C_6, A_4, A_5; A_3, A_4, A_5, A_7, C_6; A_3, A_5, A_4, B_2, A_7; A_3, A_5, A_7, B_2, A_4; A_3, A_5, A_7, A_4, B_2 separately. Based on the results of the above sensitivity analysis, the following conclusions can be drawn:

(1) Among the 28 indicators for comprehensive evaluation of urban resilience, the most sensitive ones that affect urban resilience involve four (4 out of 20) crisp indicators and two (2 out of 8) fuzzy indicators. It shows that in the comprehensive evaluation of urban resilience, it is impossible to reflect the real situation by relying only on crisp indicators, and it is necessary to consider fuzzy indicators.
(2) The urban resilience is closely related to *A* Class indicators, and the following aspects of the city need to be remediated or constructed to lift urban resilience.
(3) Among the fuzzy indicators, the ones with greater influence are A_7 climate change risk and C_6 price. Therefore, the result may give us an inspiration that climate change needs to be paid more attention on. Moreover, when a city suffers hazards, residents are likely

Table 8 Variance contribution of the 28 indicators in case study

	2013 (%)	2014 (%)	2015 (%)	2016 (%)	2017 (%)
A_1	0.015	0.005	0.008	0.033	0.008
A_2	0.026	0.036	0.028	0.071	0.019
A_3	21.351	36.181	37.457	75.161	63.024
A_4	9.879	15.312	6.373	1.959	3.843
A_5	9.786	13.515	20.505	5.247	11.366
A_6	1.134	0.293	0.549	0.233	0.338
A_7	40.533	12.673	5.322	4.751	7.586
B_1	0.046	0.003	0.020	0.004	0.007
B_2	1.794	2.895	5.860	3.435	3.572
B_3	0.011	0.001	0.015	0.004	0.006
B_4	0.002	0.021	0.007	0.032	0.006
B_5	0.002	0.046	0.009	0.012	0.006
B_6	0.711	1.958	4.663	1.580	1.981
B_7	0.202	2.590	3.172	1.030	1.038
C_1	0.005	0.026	0.059	0.004	0.097
C_2	0.271	0.898	1.914	0.429	1.023
C_3	0.100	0.627	0.843	0.101	0.646
C_4	0.304	0.774	1.920	1.023	0.564
C_5	0.662	1.996	1.905	0.838	0.534
C_6	12.192	5.930	2.649	0.604	0.811
C_7	0.007	0.503	0.099	0.028	0.139
D_1	0.489	1.346	3.410	1.108	1.084
D_2	0.027	0.001	0.010	0.062	0.015
D_3	0.029	0.150	0.009	0.003	0.008
D_4	0.002	0.001	0.011	0.029	0.040
D_5	0.008	0.027	0.009	0.006	0.004
D_6	0.308	1.083	2.412	1.432	1.414
D_7	0.107	1.111	0.780	0.787	0.833

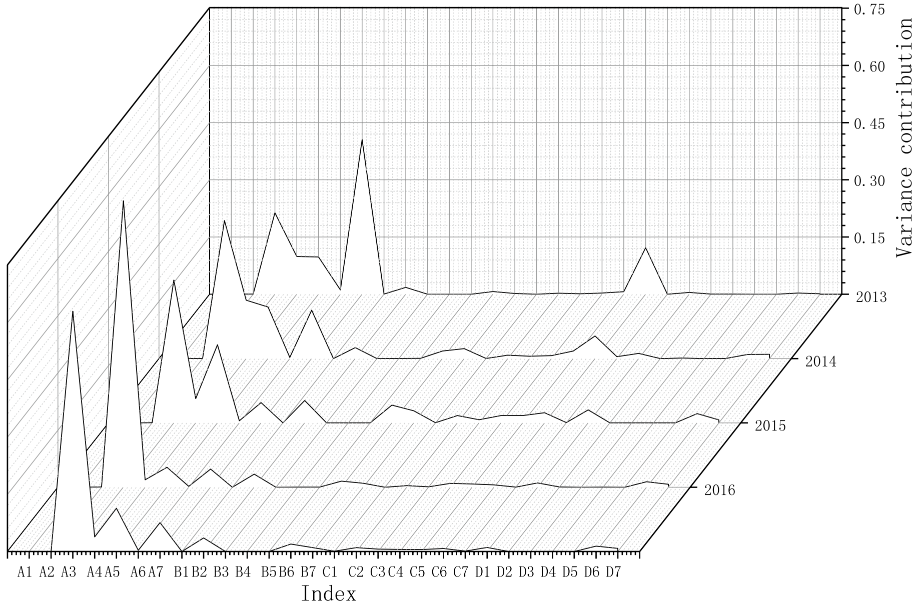

Fig. 1 Variance contribution of the 28 indicators in case study

to be pessimistic and less cooperated if prices are not stable. Thus, the government's ability to control prices is also one of the important factors for a city to get through it.

The above conclusions may provide some suggestions for the development direction of the city. But this article only made a comprehensive assessment of urban resilience from a macroscopic perspective, without taking actual disaster situations into account. Because the geographical location of each city is different, the occurrence probability of actual disasters also varies. For example, coastal cities are prone to natural disasters such as typhoons and tsunamis, and cities in plate turbulent regions are more likely to suffer from disasters such as earthquakes. Therefore, the aspects of emphasis on prevention and construction vary between cities. Meanwhile, under the context of the world's great development, hazards such as epidemics and financial crises are also unpredictable. Many hazards occur suddenly and have no obvious omen. A novel coronavirus named 2019-nCoV broke out in Wuhan, China, in December 2019 (Corman et al. 2020). In the event of such hazards, are there enough health facilities to receive patients? Can the government carry out a medical emergency plan rapidly to avoid the disease spreading into a larger scale? These abilities are closely related to the comprehensive resilience of a city, and the improvement in it is a long-term and slow process. The comprehensive urban resilience evaluation system and model proposed in this article may give suggestions to cities that have not suffered hazards beforehand.

6 Conclusions

In this paper, an evaluation indicator system for comprehensive urban resilience is established. The index system consists 4 first-level indicators of ecological environment, public facilities, economic development and social development, and 28 second-level indicators. The formation of index system is the basic and indispensable stage in the assessment of urban resilience, and it will help policy makers to discover problems and improve them during further development.

This paper proposed a hybrid multiple attribute TOPSIS method to evaluate comprehensive urban resilience, which combined the intuitionistic fuzzy method with the traditional TOPSIS method together. During the quantitative process of fuzzy indicators, the intuitionistic trapezoidal fuzzy evaluation method was used based on which the expert weights were calculated. Thus, the results were more correspond with the actual situation and improved the credibility of the evaluation process. The proposed method is applied in an example in Dalian, China, and the results show the feasibility and validity of the proposed method.

The sensitivity analysis of urban resilience evaluation based on Monte Carlo Simulation is carried out on the case study. This is a global sensitivity analysis approach, which reflects the sensitivity of the indicator through the contribution rate of the indicator variance. The results show that the six indicators with the highest sensitivity over 2013–2017 are A_3 Exhaust Emission (SO2), A_4 Number of Waste Water Treatment Facilities, A_5 Number of Waste Gas Treatment Facilities, B_2 Daily Capacity of Urban Waste Water Treatment, A_7 Climate change risk and C_6 Prices. Moreover, the result can provide guidance for city managers, planners, architects what aspects of the investment need most and more attention should be paid on climate change. At the same time, the sensitivity analysis method proposed in the article can also be used to screen a large number of evaluation indicators and help to rebuild the evaluation index system.

In further study, according to the national policy and the actual situation of a certain city, the selection of indicators can be screened and increased. Furthermore, the first-level indicators can be analyzed and compared separately, which will help policy makers to clarify the foothold of urban resilience development.

Appendix

See Table 9.

Table 9 Original data of urban resilience evaluation in Dalian from 2013 to 2017

Attribute	Data source	2013	2014	2015	2016	2017
A_1	Environmental Status Bulletin	7.32	7.18	6.63	6.55	6.14
A_2	Environmental Status Bulletin	531.11	560.91	517.85	480.9	501.52
A_3	Environmental Status Bulletin	11.93	11.08	11.22	7.92	6.68
A_4	Statistical Yearbook 12-2	523	532	483	463	363
A_5	Statistical Yearbook 12-3	1960	1960	2206	2454	1557
B_1	Statistical Yearbook 11-2	12.24	11.22	11.8	11.11	11.02
B_2	Statistical Yearbook 11-4	94	99	109	110	138.8
B_3	Statistical Yearbook 11-2	13.91	13.5	13.47	13.8	14.28
B_4	Statistical Yearbook 11-5	5249	5321	5375	5465	6220
B_5	Statistical Yearbook 11-6	2041	2088	2147	2173	2216
C_1	Statistical Yearbook 3-8	102,922	110,600	109,939	110,682	97,470
C_2	Statistical Yearbook 3-8	2916.66	3281.25	3516.39	3929.64	3497.57
C_3	Statistical Yearbook 18-4	2,943,100	3,138,534	3,505,503	2,929,176	2,750,637
C_4	National Economic and Social Development Statistical Bulletin	243	250	270.3	300	325
C_5	Statistical Yearbook 20-3	107,677,779	119,536,466	121,530,312	138,644,566	147,014,540
D_1	Statistical Yearbook 10-5	27,539	30,238	33,591	35,889	38,050
D_2	Statistical Yearbook 23-12	3839	3801	3846	4033	4145
D_3	Statistical Yearbook 24-19	250	274.3	281.9	289.1	298.2
D_4	Statistical Yearbook 24-20	129.1	136.6	138.9	139.8	140.1
D_5	Statistical Yearbook 24-21	453.1	484.8	505.4	506.7	510.1

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