

# ETM: A Method for Measuring Urban Vitality based on Entropy Topsis Model

Saijie Wang, Sirui Wang, Zhuoran Zhang, Xinying Li, Yixuan Zhao, Lei Zhang\*

School of Intelligence Science and Technology, Beijing University of Civil Engineering and Architecture, Beijing 102616, China.

\* Corresponding author: Lei Zhang (Email: lei.zhang@bucea.edu.cn)

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**Abstract:** Urban vitality is one of the key indicators of urban development, and it is crucial for assessing cities' quality and guiding urban planning. However, most of the previous studies focused on the impact of economic problems to evaluate the urban vitality, ignoring other factors. Therefore, the depiction of urban vitality often fails to adequately reflect the level of urban development. This paper builds an evaluation index system of urban vitality based on four factors: society, economy, culture, and environment. Then we analyze the spatial distribution characteristics combined with ETM (Entropy Topsis Model). Take Beijing for example, the feasibility of the model is verified by using GDP data, and it concludes that the vitality shows a circular distribution pattern of "high in the center and low in the periphery". Experimental analysis is performed to show that one single economic indicator for evaluating the suburbs vitality, while a comprehensive vitality indicator for the urban areas is more suitable to a relatively complex development structure.

**Keywords:** Urban vitality, TOPSIS, Carbon emissions, Entropy approach, Nuclear density analysis.

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## 1. Introduction

Since the reform and opening up in 1978, China's economy and society have grown quickly. The number of people living in cities has increased significantly, and economic growth has produced astounding results[1]. However, it is undeniable that China's longstanding crude growth pattern has not only exacerbated the greenhouse effect of cities, but also caused the uneven quality of urban development. In some areas, the speed of economic development is the core at the expense of the quality of development, resulting in the lack of necessary urban vitality.

Most of the current research work focuses on the impact of economic indicators on the level of urban development[2]. However, the level of urban vitality is the result of a combination of many factors. According to the existing research, the influencing factors can be divided into two categories: spatial and non-spatial factors. From the perspective of non-spatial factors, urban vitality is the result of the influence of population activities and economic factors, such as population inflow[3], GDP, consumption level[4]. From the perspective of space, urban vitality is a reflection of urban structure and scale, such as density, diversity, mixed use, accessibility, cityscape, environmental quality, and architectural form, etc.[5] The continuous increase of greenhouse gas emissions will have a significant impact on the development of the city. As the largest source of carbon emissions, city plays a key role in the realization of low-carbon sustainable development goals for the whole society[6]. Therefore, urban carbon emissions are important to the overall vitality level of the city.

At present, China's urbanization process has not yet been completed and is still in a rapid development stage. How to determine the unbalanced and insufficient status of urban development is an urgent problem to be solved. In order to solve the problem of one-sided representation of urban vitality in the current research, this paper takes Beijing as an example to explore the method of measuring comprehensive urban vitality by constructing the urban vitality evaluation

index system. This paper makes full use of POI datasets and carbon emission datasets to construct an evaluation system of urban vitality indicators from four dimensions: society, economy, culture and environment, making full use of POI datasets and carbon emission datasets. Then, Arcgis is used to visualize the results, and ETM (Entropy Topsis Model) is adopted to measure the comprehensive urban vitality. We also verify the reliability of the results by using GDP per capita data of Beijing. This study provides a research idea for the future urban development of Beijing and other regions.

The main contributions of this paper can be summarized as follows:

- The evaluation index system of urban vitality is constructed from four perspectives: society, economy, culture and environment, which has good universality. ETM is used to measure the overall vitality according to the evaluation index system.
- By contrasting comprehensive vitality and GDP data, this paper explores the differences between using one single economic indicator and composite indicators in describing urban vitality with different levels of development.
- Explore the correlation between the comprehensive city vitality and the evaluation indicators, providing a complete insight into the pattern and current situation of urban development.

## 2. Method

The ETM framework is shown in Fig.1. By organizing the obtained data, the evaluation index system is constructed from four aspects: society, economy, culture, environment. Then, the comprehensive urban vitality is measured based on ETM. Furthermore, the correlation between all vitality dimensions and comprehensive vitality is analyzed, which further verified the reliability of the experiment. To examine the differences between one single economic indicators and comprehensive indicators in measuring urban vitality, we compare trends in GDP and combined vitality by region.

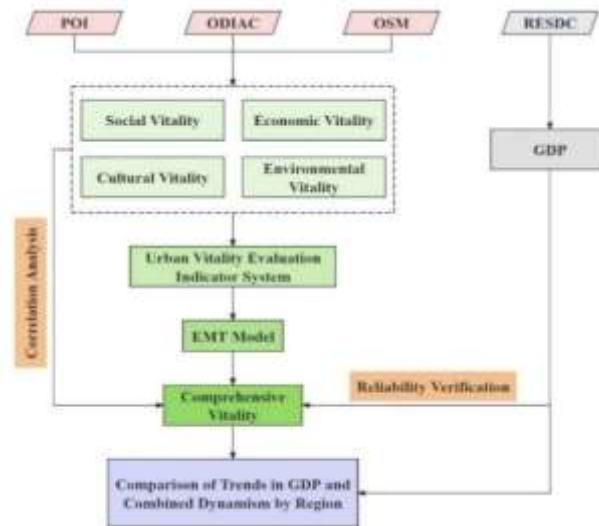


Fig 1. ETM Framework.

## 2.1. Urban Vitality Evaluation Indicator System

Social vitality is a key component of urban vitality, with human activities being fundamental to urban development. Previous research by Jacob and Montgomery posited that old buildings, small communities, density, diversity, and accessibility foster crowd aggregation, enhancing an area's urban vitality. In this study, road density, closely linked to human survival and development, is adopted to gauge social vitality[7].

Economic vitality is represented by Point of Interest (POI) data of shopping malls and restaurants. Shopping mall numbers mirror regional consumption levels and economic strength, while the distribution of catering facilities is significantly influenced by the local economy and population density, as evidenced by Wang et al.'s geographically weighted regression model. Catering facilities have a higher attrition rate and turnover, typically situated in high-traffic, multifunctional areas that are social and economic hubs. Kernel density analysis is employed to visualize POI data

distribution for a more accurate economic vitality assessment.

Cultural vitality, a multifaceted concept encompassing innovation and diversity, is challenging to quantify for innovation. Thus, cultural diversity, often represented by POI data, serves as a proxy. The density of cultural facilities is utilized as an indicator to evaluate cultural vitality.

Environmental vitality also plays an irreplaceable role in measuring urban vitality. Since the industrial revolution, carbon dioxide and other trace gases have increased by year due to excessive human activities. Carbon emissions continuously increasing trend will cause irreparable harm to the environment. As the largest source of carbon emissions, cities play a key role in achieving low-carbon sustainable development goals for the whole society. Therefore, this paper uses carbon emissions as an indicator of urban environmental vitality, and regions with high carbon emissions face challenges in environmental protection and sustainable development. After averaging the monthly ODIAC data in 2019, the spatial distribution of annual average carbon emissions in Beijing is obtained (Fig.2).

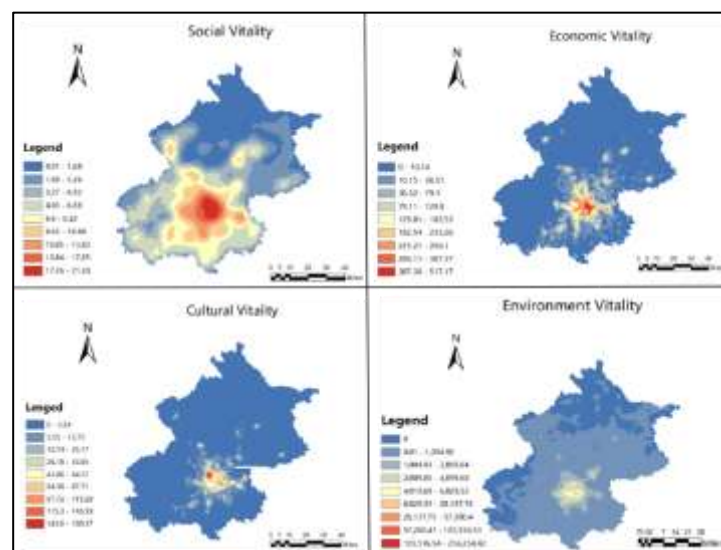


Fig 2. Spatial Distribution of Annual Average Carbon Emissions in Beijing

## 2.2. Comprehensive Vitality Measurement

Urban vitality valuation involves multiple factors and samples, which is a typical multi-criteria decision analysis problem. This paper chooses ETM to measure comprehensive vitality. The advantage of Topsis model is that there is no strict limitation on the number of indicators, sample size or data distribution. Reliable evaluation results can also be provided through simple calculations[8]. In addition, the model can also provide a basic ranking of various alternatives with intuitive geometric meanings, and can describe the comprehensive impact of multiple metrics without setting independent attribute preferences, which is intuitive, easy to implement and understand. However, the shortcomings of the model are also obvious. Since the weight of each index is the same by default, it requires the researcher to make subjective assignments during the calculation process, which increases the subjectivity of the realization results. To solve this issue, ETM is used as the entropy weighting method based on Topsis, which determines more correct and objective weight according to the information value of the original data[9].

X is the normalization matrix of the original data.

$$X = \begin{bmatrix} X_{11} & \cdots & X_{1m} \\ \vdots & & \vdots \\ X_{n1} & \cdots & X_{nm} \end{bmatrix} \quad (1)$$

where  $X_{ij}$  is the value of the j-th indicator of the i-th basic spatial unit.

Calculate the weight of each value in the column sum:

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^n X_{ij}}, j = 1, 2, 3, \dots, m \quad (2)$$

Equation (3) is the entropy value, with n is the number of objects, m is the number of indicators.

$$E_j = \frac{1}{\ln n} \sum_{i=1}^n P_{ij} \ln P_{ij}, j = 1, 2, 3, \dots, m \quad (3)$$

The weight is obtained:

$$W_j = \frac{1 - E_j}{\sum_{j=1}^m G_j} \quad (4)$$

where  $W_j$  represents the weight of j-th indicator.

Construct the weighted normalization matrix Y using Equation (5) :

$$Y_{ij} = W_j X_{ij} \quad (5)$$

The optimal and sub-optimal solutions are obtained:

$$Y^+ = (Y_1^+, Y_2^+, Y_3^+, Y_4^+) \quad (6)$$

$$Y^- = (Y_1^-, Y_2^-, Y_3^-, Y_4^-) \quad (7)$$

Calculate the distance of the evaluation object from the optimal and sub-optimal solutions:

$$D_i^+ = \sqrt{\sum_{j=1}^m (Y_j^+ - Y_{ij})^2}, i = 1, 2, 3, \dots, n \quad (8)$$

$$D_i^- = \sqrt{\sum_{j=1}^m (Y_j^- - Y_{ij})^2}, i = 1, 2, 3, \dots, n \quad (9)$$

The approximation of each research unit to the optimal solution is calculated:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}, i = 1, 2, 3, \dots, n \quad (10)$$

The final evaluation results are ranked according to the size of  $C_i$ .

## 2.3. Correlation Analysis

In order to further explore the relationship between urban comprehensive vitality and each vitality dimension, this paper uses the existing analytical data to conduct correlation analysis on each vitality dimension, and the results are shown in Fig3.

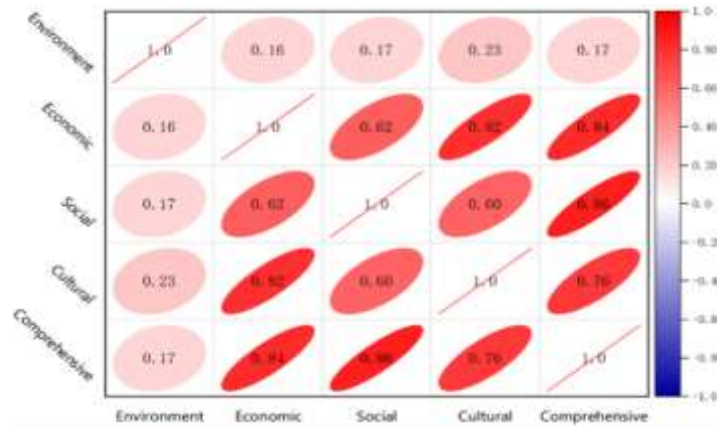


Fig 3. Correlation Analysis of Composite Vitality with the Dimensions of Vitality

It can be seen that there is a strong correlation between comprehensive vitality and social vitality, which fully demonstrates the importance of human activities in the evaluation of urban vitality. The correlation between economic vitality and comprehensive vitality is second only to social vitality. In modern cities, economic vitality is the driving force of urban vitality, representing the efficiency and material abundance, and is the economic spatial activity that contemporary cities should have[9].

## 2.4. Comparative Analysis in Measuring Urban Vitality

GDP (Gross Domestic Product) is the total market value of all final products and services produced by a country or region using its production factors in a certain period, reflecting the economic development level of the country or region in that period. We project the obtained GDP data on the map of Beijing through Arcgis, and get the distribution trend as shown in Fig.4. It can be clearly seen that the distribution trend of GDP data and comprehensive vitality are similar to

“high in the center and low in the periphery”, which not only demonstrates the feasibility of using economic indicators to

roughly evaluate the urban vitality, but also confirms the credibility of the results of this experiment[10].

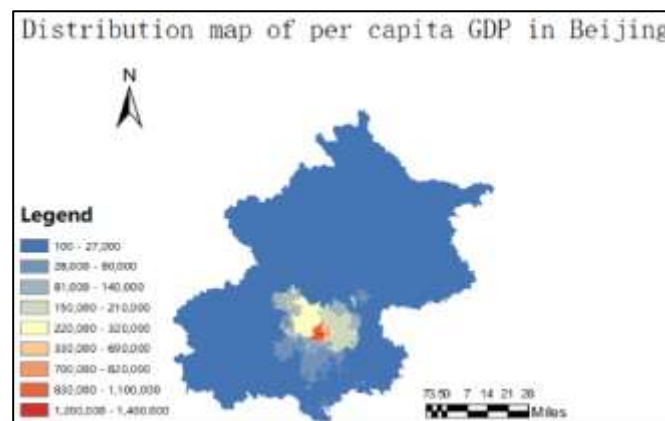


Fig 4. Distribution of Beijing's GDP per capita

In order to further explore the difference between using multiple indicators and a single economic indicator to measure comprehensive vitality, this paper calculates the average of GDP and comprehensive vitality values in each

district, and plots the average in the same coordinate system, as shown in Fig. 5. The experimental results show that the changes of GDP and comprehensive vitality do show the same trend on the whole[11].

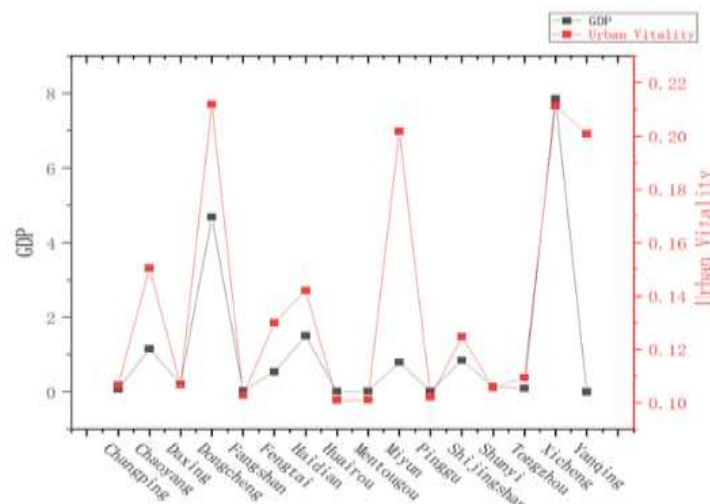


Fig 5. Comparison of Trends in GDP and Combined Dynamism by Region

However, through a detailed analysis of individual regions, we can find that the combined vitality and GDP data of cities and suburbs exhibit different numerical characteristics. The composite vitality values of urban areas differ greatly from the GDP values (Table 1), while the values of suburban areas

are very close to GDP values (Table 2 and table 3). For relatively undeveloped areas, a single economic indicator is sufficient to represent urban vitality, while for developed areas in urban centers, a single economic indicator has limited to depict urban vitality.

Table 1. Comprehensive City Vitality and GDP Comparison - Urban Areas

| Research Area          | Xicheng | Dongcheng | Haidian | Chaoyang | Shijingshan | Fengtai |
|------------------------|---------|-----------|---------|----------|-------------|---------|
| Comprehensive Vitality | 0.2113  | 0.2118    | 0.1421  | 0.1504   | 0.1247      | 0.1300  |
| GDP                    | 7.8509  | 4.6858    | 1.5019  | 1.1522   | 0.8477      | 0.5403  |
| Differences            | 7.6396  | 4.474     | 1.3598  | 1.0018   | 0.723       | 0.4103  |

Table 2. Comprehensive Urban Vitality and GDP Comparison – Suburbs

| Research Area          | Miyun   | Changping | Shunyi | Daxing | Tongzhou |
|------------------------|---------|-----------|--------|--------|----------|
| Comprehensive Vitality | 0.2017  | 0.1065    | 0.1056 | 0.1069 | 0.1094   |
| GDP                    | 0.50130 | 0.07346   | 0.1466 | 0.2255 | 0.09898  |
| Differences            | 0.2996  | -0.03304  | 0.041  | 0.1186 | -0.01042 |

**Table 3.** Comprehensive Urban Vitality and GDP Comparison – Suburbs(continued)

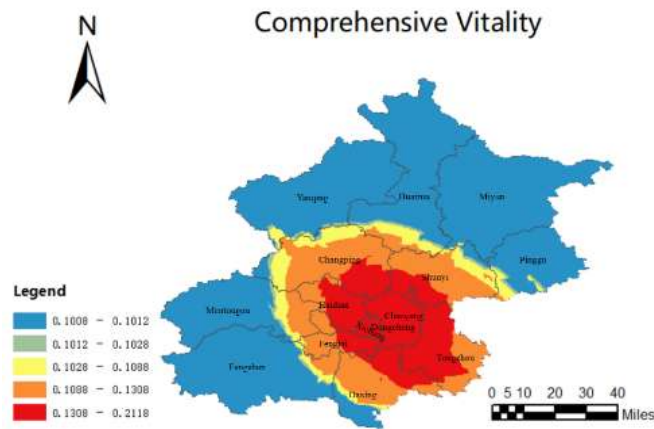
| Research Area          | Fangtai  | Mentougou | Yanqing   | Huairou  | Pinggu   |
|------------------------|----------|-----------|-----------|----------|----------|
| Comprehensive Vitality | 0.1028   | 0.1010    | 0.2008    | 0.1009   | 0.1021   |
| GDP                    | 0.03292  | 0.01693   | 0.006945  | 0.01407  | 0.02269  |
| Differences            | -0.06988 | -0.08407  | -0.193855 | -0.08683 | -0.07941 |

### 3. Results and Analysis

#### 3.1. Multi-dimensional Spatial Distribution Pattern

This paper measures the comprehensive vitality based on ETM. The results show that the comprehensive vitality of Beijing presents a decreasing spatial differentiation characteristic of decreasing from the center to the periphery, and the spatial distribution is unbalanced. As can be seen from

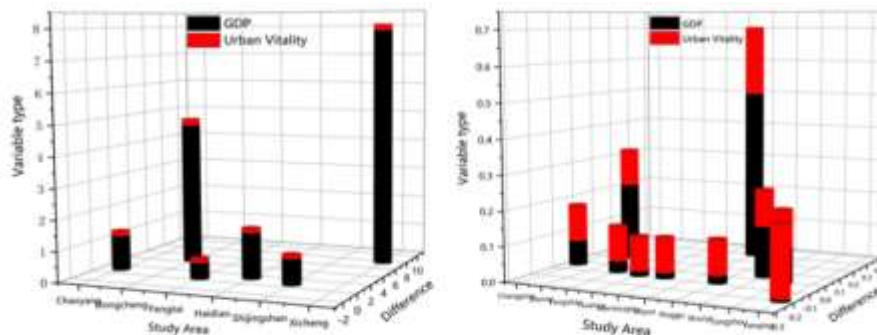
Fig 6, areas with high comprehensive vitality are mainly concentrated in Chaoyang, Haidian, Dongcheng, Xicheng, Shijingshan and Fengtai, while the vitality of other urban areas gradually decreases along the periphery. From the structural point of view, the distribution trend of the distribution of the city's comprehensive vitality has a strong similarity with the typical concentric circle structure of Beijing, which indirectly confirms that most of the economic activities in Beijing are concentrated in the urban center, and reflects the credibility of the results of this experiment.

**Fig 6.** Spatial Distribution of Multidimensional Vitality in Beijing

#### 3.2. Analytical Recommendation on Urban Vitality

In order to further explore the spatial distribution of urban vitality and verify the applicability of the results of this paper,

we study the data of Beijing urban areas (Table 3) and suburban areas (Table 4) respectively, and visualize the comprehensive vitality and GDP in different coordinate systems (Figure 7).

**Fig 7.** Difference between Combined Vitality Data and GDP for Urban (left) and Suburban (left) in Beijing

As can be seen from Figure 8, Beijing urban area is a highly developed area, and its complex development structure determines the diversity of analysis perspectives, so it will produce a large error to evaluate urban vitality only from a single economic level. For the suburban area of Beijing, because the development level of different aspects in the same region is relatively consistent, the difference of the development capacity will not have a great impact on the comprehensive effect. Therefore, it is feasible to estimate the regional vitality with economic indicators.

On the whole, the main reason for the large difference between GDP and comprehensive vitality value is environmental vitality. Among social vitality, economic vitality, cultural vitality, and environmental vitality, only environmental vitality is measured by negative samples. As can be seen in Figure 3, the carbon emissions of downtown Beijing are much higher than those of suburbs, indicating that the environmental vitality of urban area of Beijing is much lower than that of suburbs. To a certain extent, this also reduces the comprehensive vitality of the center of Beijing,

resulting in a larger gap between the comprehensive vitality and GDP. This further illustrates the importance of implementing carbon emission reduction for sustainable development.

## 4. Conclusion

This study established an evaluation system for Beijing's urban vitality from four dimensions—social, economic, cultural, and environmental vitality—and analyzed the spatial heterogeneity of its distribution, further verifying the reliability of the findings. The results indicate: (1) A multi-center structure better fosters high-vitality cities. Beijing's vitality distribution disperses from the center to the periphery, typical of Asian single-center cities. Future efforts should increase investment in non-central areas to leverage regional advantages and boost economic growth. (2) While high-density roads and facilities positively affect urban vitality, they also raise regional carbon intensity, especially in economically developed areas like high-vitality urban centers. Rational land use planning, integrating housing and employment, optimizing the urban spatial and functional layout, streamlining road design, improving public transit, and encouraging sustainable travel can mitigate commuting-related emissions. (3) Culture and environment represent a city's soft power and carrying capacity, respectively. Enhancing cultural vitality and environmental governance can invigorate regional urban vitality.

Despite the comprehensive assessment of urban vitality from social, economic, environmental, and cultural perspectives, the evaluation indicators in Table 2 have limitations. Using cultural facility density to measure cultural vitality with a single data source may yield inaccurate results due to data constraints. Future research should refine the evaluation framework and incorporate additional indicators.

## Acknowledgment

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