Study on the Coupling Coordination of Urban Infrastructure and Population in the Perspective of Urban Integration

CHENG LU, WENXIA HONG, YITING WANG, AND DEFENG ZHAO
School of Management Engineering, Qingdao University of Technology, Qingdao 266520, China
Corresponding author: Wenxia Hong (734256936@qq.com)

ABSTRACT
The continuous development of urbanization and the integration of urban agglomerations are accompanied by the outbreak of the contradiction between urban infrastructure and population. Therefore, the study of the coupling coordination relationship between urban infrastructure and population is of great significance for the benign development of cities and the in-depth integration of urban agglomerations. In order to measure the coupling coordination between urban infrastructure and population accurately and objectively, we construct the evaluation index system of urban infrastructure supply level and population development level based on biblio-metrics method, determine index weights using G1 and standard variance method, then construct a coupled coordination model from four aspects: population, infrastructure, population and infrastructure, and relative lag. Next, a case study is conducted subsequently using the Qingdao, Yantai, and Weihai in China as examples. The results show that the coupling relationship between infrastructure and population will synergistically affect urban development, and has obvious temporal characteristics. Qingdao, Yantai and Weihai have initially built the prototype of metropolitan area, changing from population development lagging city to infrastructure lagging city. The research results are of great significance to the further research of urban agglomeration integration, can provide necessary reference data for the planning and construction of Jiaodong Economic Circle, help to quantify the relevant problems in the integration process of other urban areas.

INDEX TERMS
Urban infrastructure, urban population, coupling theory, coupling coordination degree.

I. INTRODUCTION
The development process of cities can be seen as the great growth of the number of cities, the great development of the urban circle and the increasingly forming compound of the urban agglomeration, as well as the gradual maturity of the coordinated development pattern of large, medium and small cities and small towns, accompanied by the deepening of the process of regional economic and social integration and the formation of cross regional integrated governance institutions [1]. From scratch, urban agglomerations usually go through three stages: Dispersion to Concentration - Concentration to Dispersion - General Prosperity. Dispersion to Concentration is the stage of the formation of the metropolitan area, the Concentration to Dispersion is the formation period of the metropolitan belt, and the Prosperity is the development process of the urban agglomeration, and the general prosperity is the symbol of the maturity of the urban agglomeration [2]. In the 20th century, the global urban population increased from 220 million to about 2.8 billion [3]. The influx of population into cities led to the rapid expansion of urban scale [4], and the supply of urban infrastructure could not meet the basic living needs of urban population, resulting in population loss, which prolonged the cycle of “dispersion to concentration” stage of urban agglomeration [5], which in turn hindered the process of urban agglomeration moving towards metropolitan area.

The development and accessibility of urban infrastructure is poor in most developing countries [6], and as the world’s largest developing country and the world’s most populous country, China has completed the great growth of the number of cities and the great development of the urban circle, and is experiencing the compound process of urban agglomeration [7]. The contradiction between urban population and
urban infrastructure is particularly prominent at this stage, and failure to dissect the contradiction between them and refine the issues of urban infrastructure and urban population will greatly hinder the process of urban agglomeration compounding. The relevant policy work on the impact of China’s urban infrastructure on population carrying capacity has increased significantly based on the urban-agglomeration and the infrastructure development [18]. Meerow et al. [19] argued that centralization of infrastructure hinders further urbanization infrastructure innovation and instead reduces the basic standard of living of urban residents. Through the existing research, there are mainly the following deficiencies: (1) Most of the studies are directed to study how the increase of urban population affects the construction of urban infrastructure and how the lack of urban infrastructure reacts to the urban population. There are few studies to measure the relationship between the interaction and mutual influence of the two. (2) In terms of research methods, the relationship between urban infrastructure and urban population in the urbanization process is mainly studied qualitatively, and there is a lack of quantitative evaluation to study the degree of urban infrastructure supply and the coupling degree of urban infrastructure and urban population.

Therefore, it is very necessary to explore the coupling and coordination degree between urban infrastructure and urban population and the development stage of urban agglomeration from a quantitative perspective. In this paper, we will discuss the coupling mechanism of urban infrastructure and urban population, the measurement of coupling relationship, the reasons and suggestions for the current situation of coupling. Firstly, the evaluation index system of urban infrastructure supply level and urban population development level are constructed. Secondly, the coupling coordination model of urban infrastructure supply level and population is established by using the coupling coordination theory to classify the coupling coordination degree of urban infrastructure and urban population, and evaluate the coordination degree between urban infrastructure and urban population. This study helps evaluate the level of urban infrastructure supply, the level of urban population development and the degree of coupling coordination between urban infrastructure and urban population in a region, facilitates in-depth analysis of the relationship between infrastructure and population, determine the development stage of urban agglomeration.
integration, and explore the path of urban integration toward a metropolitan area.

II. LITERATURE REVIEW

A. URBAN INFRASTRUCTURE

The concept of urban infrastructure was first defined in the “Urban Infrastructure Symposium” held in 1985. It was defined as a public facility that provided both material production and general conditions for people’s lives, and the foundation for the survival and development of the city. In 1994, the World Bank explained the connotation of infrastructure in the World Development Report and proposed the general infrastructure [23]. Later, scholars and related departments present the concept of infrastructure, considered that general infrastructure includes engineering infrastructure and social infrastructure, while infrastructure in a narrow sense covers only engineering infrastructure [24]. Engineering infrastructure generally refers to energy facilities system, water supply and drainage system, transportation system, post and telecommunication system, environmental system and other engineering facilities. Social infrastructure refers to cultural and education system, medical and health system, social welfare and other facilities [25], [26]. Urbanization is always accompanied by the development of urban infrastructure, which requires huge investment and determines the structure of a city for a long time [27]. Since 1980s, Japan had accelerated the construction of infrastructure through the joint construction of infrastructure by the government and the market [28], [29]. India needs to solve the problem of insufficient funds for government infrastructure investment through PPP [30]. Canada issued a policy to establish a national infrastructure bank to overcome the severe financial and other difficulties faced by Canada’s backward infrastructure in the renewal process, and to build new infrastructure to meet the new needs of society [31]. The British government launched “green deal” in 2011 to encourage local departments and private enterprises to transform backward urban infrastructure [32]. Philadelphia was looking for a green infrastructure based approach to address the lack of drainage infrastructure, while Washington, D.C. and Glasgow established implementation portfolio solutions [33].

As the world’s most populous country, China has a particularly acute urban infrastructure problem and has therefore taken a number of policy measures. The Chinese government generally provide private enterprises with investment income by giving the float return on investment guarantee to encourage them to participate in public-private urban infrastructure development projects [34]. Since 2020, the Chinese government had adopted a bottom-up progressive planning model for the policy guidance of new infrastructure construction. This policy arrangement is a goal oriented adjustment to make the planning more adaptive and participatory, so as to improve the sustainability of infrastructure [35]. The above policies are all guiding other participants to carry out infrastructure construction, but how to coordinate the construction of the urban population with the infrastructure is more urgent.

B. URBAN POPULATION

The world’s second urban wave is underway, and the United Nations predicts that there will be 6 billion urban populations, accounting for approximately 70% of the total population by 2050 [36]. There is a close relationship between urbanization and urban population [37]. After World War II, Italy’s strong population growth accelerated the process of urbanization [38]. From 1989 to 2007, the built-up area of Sana’a, the capital of Yemen, increased by 87%, but the population almost doubled every decade, and the urban infrastructure was under great pressure [39]. The number of urban residents in Africa is expected to soar from 491 million in 2015 to nearly 1.5 billion in 2050, which brought great pressure to cities [40]. Tabuchi [41] insist that urban population growth and urban development must be coupled. Han et al. [42] claimed that the high-quality resources of cities have a siphon effect on the population, which could make the urban population scale expand rapidly and excessively in a short period of time, exceeding the appropriate population valve that cities can support in the same period. These decoupling between population and urban development could lead to a series of serious urban problems [43]. Due to the large population base and rapid population growth, China’s population urbanization rate increased rapidly from 37.7% to 54.77% from 2001 to 2014, with an average annual growth rate of 1.31%. China is now facing more pressing urban population problems, the discussion on the relationship between urban population development level and cities has never been interrupted [44]. In the forty years since China’s reform and opening up, the level of population development has been increasing constantly [45], but the relationship between urban population density and urban land is still too tense [46]. Although China’s uncoordinated urban population distribution and regional differences in urban expansion are gradually shrinking, there is still a
mismatch between provinces [47]. Ultimately, urban public safety issues [48] and excessive urban sprawl [47] seriously affect the health of urban populations and lead to urban economic decline.

C. RELATIONSHIP BETWEEN URBAN INFRASTRUCTURE AND URBAN POPULATION

The attraction of cities to population requires advanced supporting infrastructure, but the long construction cycle of urban infrastructure will slow down the expansion of urban population and urban space [49], making the migration of population in and out during the construction cycle an issue that requires special attention. Population structure and residents’ demand affect the layout of public service facilities, while urban infrastructure will also affect the development of urban population [50]. Blind urban expansion and population introduction can lead to the mismatch between urban infrastructure and urban population. In regions such as Asia, Africa, and Latin America, traditional urban infrastructure cannot cope with the challenges of rapid expansion of urban population, which hinders the process of urbanization [51]. The shortage of infrastructure in Eastern Europe led to the continuous reduction of urban population [52]. The well-developed road infrastructure in Delhi, India led to a concentrated increase in the urban population, but the backward urban infrastructure in other areas has caused slow growth in the urban population [53]. Pakistan’s population increased by 2% in 2014, which increased the pressure on energy infrastructure, and the problem of insufficient supply of energy infrastructure became more and more serious [54]. Cities in sub Saharan Africa are facing challenges such as rapid population change, high poverty and chaotic urban development process, and the supply of urban infrastructure is very scarce [55]. Northam, a famous American urban scholar, put forward the “urbanization process curve”, which holds that the relationship between infrastructure construction and population has phased characteristics in the process of urban development, can be regarded as an early reflection on the relationship between urban infrastructure and population. In the initial stage, infrastructure cannot meet the needs of population, and in the medium stage, the coordination degree between urban infrastructure construction and population shows an rising then falling trend. In the stable stage, the coupling degree between the two is maintained at a high level [56]. Zhang et al. (2014) supposed that the relationship between urban infrastructure and urban population is complex, and there is a nonlinear relationship between them showing the inverted “U” shaped structure, with the threshold effect. It suggests that in order to maximize the promotion of infrastructure to population urbanization, the infrastructure investment must maintain an appropriate scale [57]. As the largest developing country and the most populous country in the world, the contradiction between urban population and urban infrastructure is particularly prominent. Although the degree of matching between urban infrastructure supply and urban population shows a trend of increasing year by year as the amount of investment in construction infrastructure increases and the level of infrastructure per capita improves [58], the degree of matching between public infrastructure and population development is only at a medium stage [59].

The above researches are mostly attributed to the single study of urban infrastructure construction issues and urban population problem [39]–[41], which only focus on the relationship between transportation infrastructure, energy infrastructure and urban population in a single range [55], [56] analyzing the relationship between urban population and infrastructure in a qualitative way [53], [54], [57], [60]. There is a lack of quantitative evaluation research on the supply level of urban infrastructure and the development level of urban population, and the research on the coupling relationship between urban infrastructure and urban population is almost blank. Based on the above analysis, we establish the coupling coordination model of urban infrastructure and urban population, analyze the coordination and then conduct the case study to explore the relationship between infrastructure and population in the integration process of Qingdao, Yantai and Weihai, China, verify the applicability of the coupling coordination model of urban infrastructure and urban population.

III. RESEARCH METHODOLOGY

A. FRAMEWORK

As mentioned in the introduction, the purpose of this study is to develop a new method to evaluate the coupling coordination relationship between urban infrastructure and population, so as to achieve the research goal. The framework of this paper is shown below.

B. INDICATORS

1) CONSTRUCTION OF URBAN INFRASTRUCTURE INDEX SYSTEM

Urban infrastructure is the foundation for the survival and development of cities, and the urban infrastructure indicators are used to describe the carrying capacity of urban infrastructure for various social activities of the city [60], [61],
Hirschman [62] expounded the content of urban infrastructure in narrative and broad terms. From the perspective of narrative definition, the indicators of urban infrastructure are divided into several systems, such as water supply, drainage, power supply, transportation, telecommunications and so on. While from a broad perspective, social infrastructure indicators such as education and medical treatment are added on the basis of narrative definition. Lin [63] defined infrastructure indicators as hard infrastructure indicators and soft infrastructure indicators: hard infrastructure includes water supply facilities, transportation facilities, communication facilities and other physical facilities, while soft infrastructure refers to education system, legal system, social network and other intangible social and economic systems. In line with its research, Nielsen and Elle [64] conceptualized urban infrastructure into physical parts and non-physical parts. According to the definition of engineering infrastructure, we decompose the urban infrastructure into five systems: transportation facilities, energy facilities, water supply and drainage facilities, environmental facilities and communication facilities. The others are classified as social facilities. We search the keyword “Urban Infrastructure” in the Web of science, and preliminarily determines the urban infrastructure indicators through the literature reading method. The details are shown in Table 1.

In order to construct scientific and reasonable evaluation indicators, we combine the availability of indicator data and the indicator system of the China City Statistical Yearbook to accurately determine the level of infrastructure supply, and appropriately delete similar indicators, unreasonable indicators, and indicators that are difficult to obtain. For example, for the rate of sewerage disposal and the quantity of sewage treated, the rate of sewerage disposal is a more representative indicator. Only a few cities have urban rail transit, so the mileage of urban rail transit indicator is deleted.

2) CONSTRUCTION OF THE INDEX SYSTEM OF URBAN POPULATION DEVELOPMENT LEVEL

According to the existing evaluation index system of urban population development level [71]–[75], the index system of urban population development level must follow the basic principles of systematicness, integrity, effectiveness,
TABLE 1. Candidate carrier indicators retrieved in typical literature for measuring urban infrastructures capability.

| Literature | Quantity of water supply (ton) | Quantity of electricity consumption (kwh) | Utilization quantity of industrial solid waste (ton) | Quantity of sewage treated (ton) | Quantity of living garbage treatment (ton) | Hospital beds (unit) | Length of drainage pipe (km) | Number of buses (unit) | Number of buses (unit) | Urban road areas (m2) | Number of library books (volume) | Volume of living garbage harmless disposal (ton) | Number of buses (unit) | Domestic water consumption (ton) | Urban road area (m2) | Number of primary-schools’ teachers (unit) | Quantity of heat supply (kj) | The area of urban road (m2) | Quantity of water supply (ton) | Number of buses (unit) | Length of gas supply pipeline (km) | Number of telephone subscribers (unit) | Number of beds in hospitals (unit) | Water-Consuming Popularization(%) | Internet penetration rate(%) | Green Coverage Rate of Developed Areas(%) |
| ----------- | ----------------------------- | ---------------------------------------- | ----------------------------------------------- | ----------------------------- | ------------------------------------------ | --------------------- | --------------------------- | ------------------------ | ------------------------ | ------------------------- | ---------------------------------- | ------------------------------- | ------------------------ | --------------------------------- | ------------------------- | -------------------------------- | ------------------------ | ------------------------ | --------------------------- | ------------------------ | --------------------------- | ---------------------------------- | ------------------------ | ---------------------------------- | ---------------------------------- | ---------------------------------- | -------------------------------- | -------------------------------- | ---------------------------------- |
| Wei, Huang et al (2016)[65] |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Wei, Huang et al (2015)[66] |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Tian and Sun (2018)[67] |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Wang (2015) and Wang (2016)[62-63] |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Cui and Sun (2019)[68] |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| China City Statistical Yearbook |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

...
TABLE 2. Urban infrastructure supply index system.

| Sub-facility system | indicators                                      | unit   | meaning                                                                 |
|---------------------|-------------------------------------------------|--------|-------------------------------------------------------------------------|
| Energy facilities   | Gas penetration rate                            | %      | The ratio of the urban population using gas to the total urban population. |
|                     | Per capita annual domestic power consumption    | kWh    | Reflecting the economic development and people’s living conditions in the administrative region. |
|                     | Per capita daily consumption of tap water        | L      | Reflecting the local water consumption situation.                       |
|                     | Per capita daily consumption of tap water for residential use | L      |                                                                 |
| Water supply and drainage facilities | Water supply penetration rate | %      | Reflecting the local water supply situation.                            |
|                     | Density of drainage pipeline in developed area   | km/k   | Reflecting the local drainage situation.                                |
|                     | Rate of sewerage disposal                       | m2     | Reflecting the local drainage capacity.                                 |
|                     | Urban Road area per capita                      | m2     | Reflecting whether the road area in a certain administrative area is reasonable. |
| Transportation facilities | Number of bus per 10000 population | unit   | Reflecting the level of public transport development in the area.       |
|                     | Number of taxi per 10000 population             | unit   | Reflecting the local transportation service level.                     |
| Communication facilities | Mobile phone penetration rate | %      | Reflecting the local communication level.                               |
|                     | Internet penetration rate                       | %      | Reflecting the local communication level.                               |
|                     | Number of public books per population           | piece  | Reflecting the level of local culture and cultural construction.        |
| Social infrastructure | Number of beds in health institutions per 10000 population | unit   | Reflecting the level of local medical services.                        |
|                     | Per capita park green areas                     | m2     | Reflecting the local environmental conditions.                         |
| Environmental facilities | Green coverage rate of developed areas | %      | Reflecting the local environment.                                      |
|                     | Public toilets per 10000 population             | unit   | Reflecting the city’s environment.                                     |

IV. ESTABLISH THE COUPLING COORDINATION MODEL BETWEEN URBAN INFRASTRUCTURE AND POPULATION

A. USE G1 METHOD TO DETERMINE THE WEIGHT OF URBAN INFRASTRUCTURE INDICATORS

The G1 method is a subjective weight determining method. In this method, the index weight is determined by first sequencing the index importance and then followed by estimating the relative degree of importance between the adjacent sequenced indexes. It is upgraded from the AHP method, and has resolved the disadvantages of the previous large and complex calculations and the required consistency checks [69]. Considering that the G1 method is a subjective weighting method for index weights, it can make full use of the rich knowledge and practical experience of decision-making experts [70], and there are many subjective indicators in the evaluation system of urban infrastructure, therefore, we adopt the G1 method to calculate the subjective weight of the urban infrastructure supply level and population development level. The specific steps are as follows:
TABLE 3. Candidate carrier indicators retrieved in typical literature for measuring the level of urban population development.

| Literature          | Urban population indicators                                                                 |
|---------------------|---------------------------------------------------------------------------------------------|
| Zhao and Chai(2015) | Population density                                                                          |
|                     | Population urbanization rate                                                                 |
|                     | Proportion of non-agricultural working population                                            |
| Chen et.al.(2010)   | Proportion of urban population                                                                |
|                     | Urban population size                                                                        |
| Zhang et.al.(2018)  | Labor force in secondary and tertiary industries                                              |
|                     | Population density in built-up area                                                           |
|                     | Proportion of urban population                                                                |
|                     | Size of urban population                                                                      |
|                     | Percentage of nonagricultural population                                                      |
| Ding et.al.(2015)   | Urban population density                                                                      |
|                     | Percentage of second industry employment                                                      |
|                     | Percentage of tertiary industry employment                                                     |
|                     | Urban population                                                                              |
|                     | Proportion of urban population in total population                                            |
|                     | Proportion of nonagricultural employment                                                       |
| Shi et.al.(2020)    | Urban population density                                                                      |

Step1. Rank the importance of indicator

\[ X_1^* > X_2^* > \ldots > X_{j-1}^* > X_j^* > \ldots > X_n^* \]  

between the evaluation index \( X_i^* \) \( (i = 1, 2, \ldots, n) \) and a benchmark layer (target layer) according to the evaluation system.

Step2. Calculate the relative importance of neighboring indicators

\[ \frac{w_{j-1}}{w_j} = r_j, \quad j = n, \ n-1, \ n-2, \ldots, 3, 2 \]  

Step3. Calculate the weight coefficient \( w_i^* \).

\[ w_i^* = \left( 1 + \sum_{j=2}^{n} \prod_{k=j}^{n} r_k \right)^{-1} w_{j-1}^* \]  

\[ w_j^* = \frac{r_j w_j}{w_{j-1}}, \quad j = n, \ n-1, \ n-2, \ldots, 3, 2 \]

B. DETERMINING THE INDEX WEIGHT OF URBAN POPULATION DEVELOPMENT LEVEL BY VARIANCE WEIGHTING METHOD

To calculate the urban population development level, it is necessary to avoid deviation due to subjective factors as much as possible. Considering the quantitative characteristic of the variance weighting method and the indicators of population development level are already determined, all data are objective data, the variance weighting method with large amount of calculation but convenient operation and enough data processing is the best choice. The calculation formula is as follow.

Step1. Calculate standardized value \( Y_{ij} \).

\[ Y_{ij} = \begin{cases} \frac{X_{ij} - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}} & \text{if} \quad X_{ij} \leq X_{\text{max}} \\ 1 - \frac{X_{\text{max}} - X_{ij}}{X_{\text{max}} - X_{\text{min}}} & \text{if} \quad X_{ij} > X_{\text{max}} \end{cases} \]

where \( X_{ij} \) is the original value of index \( i \), \( X_{\text{max}} \) and \( X_{\text{min}} \) is the minimum and maximum values of \( E_i \), which is the mean value of random variable and can be calculated by Eq(5) as follows.

\[ E_i = \frac{1}{n} \sum_{j=1}^{n} Y_{ij} \]

Step2. Calculate the mean square deviation of indicators \( \sigma_i \) using Eq(6).

\[ \sigma_i = \sqrt{\frac{1}{n} \sum_{j=1}^{n} (Y_{ij} - E_i)^2} \]

Step3. Calculate the weight coefficient \( w_i \) using Eq(7).

\[ w_i = \frac{\sigma_i}{\sum_{i=1}^{m} \sigma_i} \]

C. MEASUREMENT MODEL OF URBAN INFRASTRUCTURE LEVEL

Perform dimensionless processing on the indicators. The indicators in this paper are all positive indicators, so the dimensionless process is conducted using Eq(8).

\[ x_{ij} = \frac{C_{ij}}{D_j} (0 \leq C_{ij} \leq D_j, \quad \text{and make} \quad C_{ij} = D_j \text{ if } C_{ij} > D_j) \]
where $C_{ij}$ is the original data value of the $j$-th index, $D_j$ is the standard value of the $j$-th index, $x_{ij}$ is the value of the $j$-th index after eliminating the dimensional difference.

Specially, if the value of $j$ is greater than the standard value, the index is considered to meet the urban infrastructure level standard, which can be expressed as $C_{ij} = D_j$.

In this paper, a linear weighting method is used to construct an evaluation model for the supply level of urban infrastructure $h(x_j)$ as $\text{Eq}(9)$.

$$h(x_j) = \sum_{j=1}^{n} w_j \cdot x_{ij} \quad (1 \leq i \leq m, 1 \leq j \leq n)$$

**D. MEASUREMENT MODEL OF URBAN POPULATION DEVELOPMENT LEVEL**

Since we not focus on analyzing which factors have a greater impact on urban population but to conduct a comprehensive measurement based on the selected indicators, we select a simple linear weighted sum method to carry on the next steps as $\text{Eq}(10)$.

$$g(y_j) = \sum_{i=1}^{m} Y_{ij} \cdot w_i$$

**E. COUPLING COORDINATION MODEL OF URBAN INFRASTRUCTURE AND POPULATION**

The coupling coordination analysis is a kind of quantitative analysis for the association degree between two or more systems. It can measure the close relationship between the systems and the process and extent of the development caused by a specific object [76], [77]. The coupling coordination analysis of urban infrastructure and population refers to the relationship between urban population and infrastructure, as well as the relationship between urban population development level and infrastructure supply. Coupling is to comprehensively analyze the coordinated changes between different variables based on system theory, without considering the causal relationship. Coupling reflects the two states of development and coordination. Development refers to the evolution and development of the system, usually from low to high, from simple to complex, while coordination represents the interrelationship between the system and the elements within the system. The coupling theory mainly includes the following three models.

1) **SYSTEM DEVELOPMENT MODEL**

$$T = \alpha h(x_i)^\theta g(y_j)^{1-\theta}$$

where $h(x_i)$ is the supply level of urban infrastructure, $g(y_j)$ is the development level of urban population, $\alpha$ is an exogenous parameter, $\theta$ and $1-\theta$ is the output elasticity of urban infrastructure and population subsystem respectively, reflecting their importance relative to the total system.

2) **SYSTEM COORDINATION MODEL**

Coordination degree $C_v$ is used to measure the cooperation between systems, which can be express as $\text{Eq}(12)$.

$$C_v = \sqrt{\frac{(h(x) - g(y))^2}{2}}$$

The smaller the value, the smaller the deviation of the two systems, that is, the coordination between urban infrastructure and urban population is good. When $C_v = 0, h(x) = g(y)$, it indicates that the two systems are in the best coordination state; When $h(x) < g(y)$, it means that the urban population system deviates greatly from the urban infrastructure system; When $h(x) > g(y)$, it indicates that the urban infrastructure system deviates greatly from the urban population system.

3) **COUPLING COORDINATION MODEL**

In the coupling coordination model (Fig.7), focusing only on the coupling development status between systems can lead to poor coordination of the system, while focusing only on the coordination can also be detrimental to the mutual development. Coupling is a combination of development and coordination, so the coupling coordination degree contains a comprehensive measure of both the development and coordination dimensions of the system. Coordination $D$ can be calculated by $\text{Eq}(13)$.

$$D = \sqrt{C \cdot T}$$

In Fig.7, T1, T2, T3 is the iso-development lines, OO’, AA’, BB’ is the iso-coordination lines. OO’ is the optimal coordination line. The intersection of the coordination line and the development line can be used to describe the coupling level of the system. The population development level of the H and G in the above Fig.7 is the same, and the coordination of G is higher than H. The reason is that the urban infrastructure and the urban population subsystem at H have a certain degree of deviation, indicating their lack of cooperation. That is, the low development trap caused by focusing only on coupled coordination dynamics. The coordination degree between F and G is the same, but the
The classification of the coupling coordination evaluation levels can diagnose whether the urban infrastructure and population development level is healthy, and clarify the problems and limitations between the urban infrastructure and population, explore suitable solutions subsequently. There are two main methods for the division criteria and types of coupling coordination degree: quartile method and uniform distribution function method. On this basis, this paper refines the coupling coordination state, the coupling and coordination evaluation results of urban infrastructure and urban population development level are divided into eight levels according to the existing research (Table 4).

| Index levels | Coupling          | Coordination       | Coupling coordination types                |
|--------------|-------------------|--------------------|--------------------------------------------|
| 0.0–0.12     | Extreme decoupling| Extreme incoordination | Extreme disorder type                      |
| 0.13–0.25    | Serious decoupling | Serious incoordination | Serious disorder type                      |
| 0.26–0.37    | Moderate decoupling| Moderate incoordination | Moderate disorder type                      |
| 0.38–0.50    | Mild decoupling   | Mild incoordination | Mild disease type                          |
| 0.51–0.62    | Primary coupling  | Primary coordination | Primary coupling coordination type          |
| 0.63–0.75    | Moderate coupling | Moderate coordination | Moderate coupling coordination type         |
| 0.76–0.87    | Favorable coupling | Favorable coordination | Favorable coupling coordination type        |
| 0.88–1.0     | Quality coupling  | Quality coordination | Quality coupling coordination type          |

The Qingyanwei Area is the abbreviation of Qingdao, Yantai and Weihai. On January 4, 2011, the State Council of China approved the development plan of Shandong Peninsula Blue Economic Zone, which marks the implementation stage of the national marine economic development pilot work and the official rise of the construction of Shandong Peninsula Blue Economic Zone into a national strategy and an important part of the national marine development strategy and regional coordinated development strategy. As an important part of Shandong Peninsula (Jiaodong Peninsula), the Qingyanwei area is the core area of Shandong Peninsula Blue Economic Zone and one of the

4) RELATIVE LAG MODEL

Eq(14) can further reveal the relationship between the coordinated development degree of infrastructure and population, calculate the relative lag between them.

\[ N = h(x_j) - g(y_j) \]  

where \( N \) is the lag index. When \( N = 0 \), it means that the infrastructure and population development model are in an ideal state, that is, they are synchronized and coordinated; when \( N < 0 \) indicates that the comprehensive level of infrastructure lags behind the comprehensive level of population, which can be defined to the infrastructure lagging stage. On the contrary, when \( N > 0 \), it is the population lagging stage.

V. CASE STUDY

A. STUDY AREA

The Qingyanwei Area is the abbreviation of Qingdao, Yantai and Weihai. On January 4, 2011, the State Council of China approved the development plan of Shandong Peninsula Blue Economic Zone, which marks the implementation stage of the national marine economic development pilot work and the official rise of the construction of Shandong Peninsula Blue Economic Zone into a national strategy and an important part of the national marine development strategy and regional coordinated development strategy. As an important part of Shandong Peninsula (Jiaodong Peninsula), the Qingyanwei area is the core area of Shandong Peninsula Blue Economic Zone and one of the
TABLE 5. Urban infrastructure evaluation index weights and standard values.

| Sub-facility system                  | weight | indicators                              | weight | Standard value |
|--------------------------------------|--------|-----------------------------------------|--------|----------------|
| Energy facilities                    | 0.0483 | Gas penetration rate                     | 0.062  | 100            |
|                                     |        | Per capita annual domestic power consumption | 0.065  | 1000           |
| Water supply and drainage facilities | 0.3947 | Per capita daily consumption of tap water for residential use | 0.072  | 200            |
|                                     |        | Water supply penetration rate            | 0.064  | 100            |
|                                     |        | Density of drainage pipeline in developed area | 0.059  | 20             |
|                                     |        | Rate of sewerage disposal                | 0.067  | 100            |
| Transportation facilities            | 0.1768 | Urban Road area per capita               | 0.063  | 15             |
|                                     |        | Number of bus per 10000 population       | 0.07   | 20             |
|                                     |        | Number of taxi per 10000 population      | 0.059  | 20             |
| Communication facilities             | 0.0777 | Mobile phone penetration rate            | 0.061  | 100            |
|                                     |        | Internet penetration rate                | 0.058  | 100            |
| Social infrastructure                | 0.0567 | Number of public books per population    | 0.055  | 5              |
|                                     |        | Number of beds in health institutions per 10000 population | 0.06  | 100           |
| Environmental facilities             | 0.246  | Per capita park green areas              | 0.064  | 20             |
|                                     |        | Green coverage rate of developed areas   | 0.061  | 45             |
|                                     |        | Public toilets per 10000 population      | 0.06   | 12             |

most developed areas in China. As of 2019, the Qingyanwei Area has a population of 18.6 million people, accounting for 1.3% of the country’s total population, with a built-up area of 1296.57 km² and a GDP of 2,235.7 billion yuan. The reasons for selecting the Qingyanwei area of China as the research object are as follows. (1) The practical experience of urban integration is sufficient. In 2020, Shandong Province made a clear plan for the integrated development of Jiaodong Economic Circle. Shandong Peninsula Blue Economic Zone is the predecessor of Jiaodong Economic Circle, and Qingdao, Yantai and Weihai are the core cities of Shandong Peninsula Blue Economic Zone, which has been practiced in terms of urban integrated development for many years. (2) The contradiction between urban infrastructure and urban population is prominent. Although the Qingyanwei Area has a high level of urbanization, dense urban population and relatively complete urban infrastructure, the contradiction between urban population and infrastructure is increasing, which hinders the development of Qingyanwei Area into a metropolitan area. (3) The strong development potential. In the future, the main objects of China’s urbanization process will focus on the metropolitan area in the eastern coastal area, and Qingyanwei area is the most dynamic metropolitan area in the eastern coastal area.

B. DETERMINE THE INDEX WEIGHT AND STANDARD VALUE OF URBAN INFRASTRUCTURE AND POPULATION

After processing the data, we determine the weight of each evaluation index of urban infrastructure according to the calculation steps of G1 method and obtain the weight of each evaluation index, as shown in Table 5.

In order to meet the basic living needs of the urban population, the Water supply penetration rate should be 100%. Calculate the Per capita annual domestic power consumption in large cities with relatively complete infrastructure such as Beijing, Shanghai, Guangzhou and Shenzhen. The weighted average value is 1000KWh, so the standard value of this indicator is determined to be 1000KWh. According to the statistics, the Per capita daily consumption of tap water for residential use of more than 5 million cities in China is calculated as 168L. Considering the imbalance of urban development and the insufficient supply of infrastructure, the standard value of this index is set as 200L. According to more than 5 million cities in China, the density of drainage pipeline in developed area of China’s urban statistical yearbook is 15km/km², and this index is increased to 20km/km². In order to build an environmentally friendly city, the standard value of rate of sewerage disposal should be 100%. The target value of the urban road area per capita in the construction of a well-off society in China is 12km², and the average value of this indicator in developed countries has reached 20km². Therefore, the standard value of urban road area per capita in cities in China is adjusted to 15m². China stipulates that the national class a standard for civilized cities is 12 buses per 10,000 people, so this standard is set as 12 units. The average number of taxi per 10,000 population in more than 5 million large and medium-sized cities in China is 15unit, which is raised to 20unit accordingly. In order to meet the basic communication requirements, the penetration rate of mobile phone and penetration rate of Internet should reach 100%. In 2017, China’s public book collection reached 970 million books, less than 1 per capita. The average Number of public books per population in large and medium-sized cities with
more than 5 million in China was calculated to be 2.5 books. Taking into account the increasing demand for Chinese culture, the standard was raised to 5 volumes. Shanghai and Beijing, the cities with the richest medical resources in China, had 74 health institutions per 10,000 population in 2010, the number of health institutions per 10,000 population in China is 60 in 2020. Taking into account the scarcity of medical resources in China’s cities, the standard value is raised to 100. According to the Eco-City Green Paper published by the Chinese Academy of Social Sciences in 2018, the top ten eco-cities in China are Shenzhen, Guangzhou, Shanghai, Beijing, Nanjing, Hangzhou, Zuhuai, Xiamen, Tianjin, and Ningbo. According to these ten cities, the weighted average yields a Per capita park green areas of 20m², and the standard value of this indicator is 20m². The weighted average yields a green coverage rate of 48% in the built-up area, so the standard value of this indicator is taken. In 2014, the public toilets per 10000 population in Chinese cities was 2.8 units, which is obviously low. According to statistics, the Public toilets per 10000 population in Chinese cities of more than 5 million people is 12 units. In addition, due to the continuous influx of population into large and medium-sized cities, so we increased the value to 15 units.

After processing the data, the weight of each evaluation index of urban population development level is determined according to the calculation steps of variance weighting method, and the weight of each evaluation index is obtained as shown in Table 6.

### TABLE 6. Evaluation index weight of urban population development level.

| Evaluation Index of Urban Population Development Level | Qingdao | Yantai | Weihai |
|--------------------------------------------------------|---------|--------|--------|
| Percentage of second and tertiary industry employment | 0.243   | 0.238  | 0.237  |
| Urbanization rate                                      | 0.270   | 0.253  | 0.270  |
| Size of urban population                               | 0.243   | 0.254  | 0.250  |
| Urban population density                               | 0.243   | 0.254  | 0.243  |

D. RESULTS AND DISCUSSION

#### 1) URBAN INFRASTRUCTURE SUPPLY AND POPULATION DEVELOPMENT LEVEL

First of all, it can be seen from Fig.9(a) that the urban infrastructure supply level of Qingdao, Yantai and Weihai in 2010-2019 generally showed a steady upward trend. Compared with Qingdao and Yantai, Weihai has a higher infrastructure supply level, which tends to increase over time. The overall development level of infrastructure between Qingdao and Yantai in the past decade is not much different, but the development trend of Yantai fluctuates more, showing a W shape, which slightly surpassed Qingdao in 2013 and 2015. A series of clearly oriented policies issued by the Chinese authorities are the main reason for this significant upward trend mentioned above. Particularly, the development plan of Shandong Peninsula Blue Economic Zone approved by the China’s State Council in 2011 has set up special funds for public infrastructure construction, which has effectively promoted the construction of urban infrastructure and the development of social carrying capacity. As the first national sanitary city and garden city in China, Weihai has a small urban volume and is a later built city with more modern urban transportation and urban environment, the environmental infrastructure and water supply and drainage infrastructure are in a leading position in China. In addition, the urban rail transit is not taken into account in this paper. Therefore, the urban infrastructure level of Weihai City is higher than that of the other two cities. Meanwhile, the main city of Qingdao was built earlier, with dense urban buildings, backward urban water supply and drainage infrastructure, and narrow urban main roads. Yantai has eliminated some backward energy infrastructure, and the construction process of transportation infrastructure and social infrastructure is relatively slow. This
has led to a lower level of infrastructure supply in Qingdao and Yantai than in Weihai.

Secondly, Fig.9(b) shows that the urban population development level in Qingyan, Yantai and Weihai spans a wide range in the time dimension and the urban population development level changes sharply. Specifically, the urban population development level of Yantai is higher than the other two cities but has a tendency to be surpassed, the overall growth trend of urban population development level of Weihai is less stable but develops rapidly with a W-shape in general, and the population development level of Qingdao grows more steadily which is the lowest among the three cities with a small gap. From a realistic point of view, the rapid improvement of urban population development level in the three cities mainly benefits from good urban foundation and unique location advantages. Qingdao, Yantai and Weihai have good urban infrastructure and obvious geographical advantages as a coastal city, coupled with a good ecological environment and profound history and culture, there is an obvious attraction effect on the population, resulting in a steady increase in the urbanization rate. Although the population of the city is growing fast, the continuous expansion of the built-up area of the city makes the population density of the city decreasing, and with the optimization of the industrial structure, the proportion of people employed in secondary and tertiary industries increases rapidly. Yantai has a lower cost of living than Qingdao and a more developed urban development and economy level than Weihai, but due to the largest proportion of rural population among the three cities, coupled with the fact that China began to officially implement the national rural revitalization strategy plan after 2018, which limited the rate of transition from rural to urban population, resulting in the urban population development level being overtaken by Qingdao and Weihai in 2019. The main factor limiting the development of urban population in Weihai is the number of urban population. Among the three cities, Weihai has the smallest population and only Weihai has an outflow of population, resulting in an unstable level of urban population development in Weihai. Qingdao city is socially and economically developed, and the population density of Qingdao city is 1.5 times that of Yantai city and twice that of Weihai city, so it is relatively more difficult to enhance the population development than other cities.

2) COUPLING COORDINATION DEGREE BETWEEN URBAN INFRASTRUCTURE AND POPULATION

Fig.10 shows that the coupling and coordination degrees of urban infrastructure and urban population in Qingdao, Yantai and Weihai have obvious temporal characteristics, and grow positively with time. The development process of the transition from the primary coupling coordination stage to the good coupling coordination stage of urban infrastructure and population in Qingdao, Yantai and Weihai can be divided into three stages. The first stage is 2010-2012, the primary coupling state. In this stage, Shandong Peninsula Blue Economic Zone began to make preparations, and investment in urban infrastructure construction increased, the urban infrastructure level of the three cities increased from 0.62 to 0.64, the urban population development level increased from 0.62 to 0.64, the coupling coordination degree increased from 0.26 to 0.33, the coupling coordination degree increased from 0.58 to 0.64, and began to enter the initial stage of improvement. The second stage is 2012-2015, the middle-level coupling stage. Shandong Peninsula Blue Economic Zone enters a comprehensive construction stage, urban infrastructure construction and transformation have developed continuously, urban infrastructure construction level had raised to 0.66, the scale growth of urban population and employment...
structure improvement is accelerated, urban population development level had raised to 0.5, coupling coordination degree increased to 0.75, entering a stable development stage. The third stage is 2015-2019, the good coupling stage. All aspects of the construction of the Blue Economic Zone of Shandong Peninsula have entered the final stage. In the past decade of development, most of the urban infrastructure construction of the three cities have been completed, the infrastructure supply level increased to 0.7, the urban population development level increased to 0.75, and the coupling coordination degree reached 0.85. With the synchronous development of urban infrastructure and urban population, the coupling coordination degree reached a good state, and the three cities have officially entered the all-round integrated development.

The above analysis shows that the three cities have carried out the initial integrated development under the policy support of Shandong Peninsula Blue Economic Zone, the coupling coordination degree of urban infrastructure and population improved synchronously and stably, and the urban agglomeration is more complex. It took ten years to complete the Dispersion to Concentration stage and to create the prototype of metropolitan areas. In 2020, based on the achievements of the three cities, Shandong Province issued a medium-term development policy to build the Jiaodong Economic Circle with Qingdao, Yantai, Weihai as the core, benchmarking with international metropolitan areas such as the Yangtze River Delta and the Pearl River Delta. The development goal of the three cities in the future is to improve the well-quality coupling coordination state of urban infrastructure and population to a high-quality state, mature the pattern of coordinated development of large, medium and small cities and towns within the city cluster, and enter the “general prosperity” stage of city cluster development.

3) RELATIVE LAG OF URBAN INFRASTRUCTURE AND POPULATION

It can be seen from Fig. 11 that from 2010 to 2016, the urban infrastructure supply level of the three cities of Qingdao, Yantai and Weihai was greater than the urban population development level, which indicate that these three cities are population development lagging city. During this period, the supply of urban infrastructure construction of the three cities began to fall behind the level of population development, and the capacity of urban infrastructure carrying population began to shrink slowly. In 2017, Yantai was the first of the three cities to become a infrastructure lagging city, followed by Qingdao in 2018 and Weihai in 2019. With the steady growth of the economic level of Qingdao, Yantai and Weihai, the population development level will maintain the growth trend. However, due to the long infrastructure construction cycle, if the urban infrastructure can not be planned in advance, the lagging state of the infrastructure can not be changed in the short term.

In general, in the process of building the prototype of metropolitan area, Qingdao, Yantai and Weihai have changed from population development lagging city to infrastructure lagging city. Although the coupling coordination degree of urban infrastructure and population has been in the well coordination state, the lag of infrastructure is bound to hinder the development process from Jiaodong Economic Circle to the general prosperity stage of international metropolis.

VI. CONCLUSION

The coordination between urban infrastructure and population directly affects the regional economic development and the integration process of urban agglomeration. Therefore, the research on the coupling relationship between urban infrastructure and population has important reference value for judging the development stage of urban agglomeration. In this paper, a coupling coordination model based on panel data is proposed to measure the coupling between urban infrastructure and population. First, the evaluation index systems of urban infrastructure supply level and urban population development level are established through the literature research method. The G1 method is used to conduct the index weight of urban infrastructure to make the analysis of objective panel data take into account subjective factors, and the variance weighting method is used to calculate the index weight of urban population development level, so as to ensure the reliability of objective indicators, then combine them by linear weighting method. Secondly, a coupled coordination...
model between urban infrastructure and population is constructed based on the coupled coordination theory, forming a more comprehensive measurement from four aspects: system development, coordination, coupling and relative lag. Finally, the panel data of relevant indicators of Qingdao, Yantai and Weihai are used to measure urban infrastructure, urban population and the coupling coordination and relative lag between them from 2010 to 2019, judge the stage of urban integration development and make suggestions on the urban development process.

The main conclusions of this paper are as follows.

Firstly, there do exist a complex coupling relationship between urban infrastructure and population, and urban development is affected by the synergy of urban infrastructure and urban population. The indicator system of urban infrastructure and population development level constructed through literature research and indicator screen shows that urban infrastructure is constrained by multiple factors such as transportation, environment and energy, and urban population has a strong correlation with city size and employment structure. A well-developed urban infrastructure attracts urban population, and the influx of urban population leads to an insufficient supply of urban infrastructure, which in turn hinders the compounding process of urban agglomerations. China’s current level of urban development is generally stable and rapid, but there are still problems such as mismatch between urban infrastructure and urban population, which affects the sustainability of urban development and hinders the integration process of urban agglomerations.

Secondly, the case study shows that Qingdao, Yantai and Weihai have initially created the prototype of a metropolitan area, completing the stage of dispersion to concentration. Specifically, the supply level of urban infrastructure in the three cities generally shows a steady upward trend. Although there are occasional fluctuations, it is in a state of steady increase and improvement year by year. The coupling coordinated development of urban infrastructure and population has obvious temporal characteristics in the meanwhile. The coupling coordination degree increases in a positive trend with time, from the primary coupling coordination state to the well coupling and coordination state. In addition, the level of urban infrastructure supply in the region was greater than urban population development from 2010 to 2016, making it a population development lagging city and gradually changing to a infrastructure lagging city in 2017. The coupling coordination degree of urban infrastructure and population have developed synergistically, laying a solid foundation for the next step of building the Jiaodong Economic Circle as an international metropolitan area, but the transformation from population development lagging city to infrastructure lagging city has become a new obstacle.

VII. SUGGESTION

Firstly, the study on the coupled coordination degree of urban infrastructure development and urban population conducted in this paper uses linear interpolation method to supplement the data indeed in the China Statistical Yearbook according to the mathematical model, which inevitably causes certain errors. In addition, at the indicator system building stage, the indicators which data are not available and with large disparity between cities are removed according to the data availability principles of indicator selection, resulting in the difference between the actual and ideal indicator system, lead to a certain degree of deviation in the research results. Besides, we take the total urban infrastructure as the starting point for analysis, does not discuss the urban infrastructure subsystem, which cannot elaborate the impact of urban infrastructure on urban population and the coupling coordination between various types of urban infrastructure and population in detail.

Secondly, due to the difficulty of calculation and time, we only select three core cities in the Blue Economic Zone of Shandong Peninsula in China for case study, and fails to cover more cities. Future research could focus on expanding to all cities in Jiaodong Economic Circle, investigate the coordinated development state of the whole metropolitan area, form a more comprehensive research and provide reference for Jiaodong Economic Circle to reach the general prosperity stage.

In the era of urban agglomerations led by central cities and metropolitan areas, the spatial layout of interconnected and overlapping development patterns of metropolitan areas and cross-regional urban agglomerations is increasingly formed, and urban agglomerations have gradually broken the boundaries of administrative divisions. In the initial decentralization to concentration stage, the process of establishing the prototype of a metropolitan area, the level of infrastructure and population development of urban agglomerations should be co-located and synchronized, allowing for the integration of urban agglomerations in terms of regional and urban standards. In the medium-term centralized to decentralized stage, the focus should be on promoting the development of industrial chain clusters among urban agglomerations, achieving collaborative governance of multiple urban entities to create an urban cluster development community. In the general prosperity stage, urban infrastructure, population, economy and system will be developed in synergy to create a metropolitan area integrating region, standard and development, become an urban agglomeration of national and even global economic growth pole.

REFERENCES

[1] Y. L. Tang, “Constructing the spatial layout strategy system of the modern socialist country in the new era: Based on the investigation of urbanization development,” J. Tongji Univ., Social Sci. Sect., vol. 32, pp. 45–54, 2021.
[2] J. X. Mi, “Comparison of characteristics of China’s three major economic circles from the perspective of world urban agglomeration,” J. Commercial Econ., vol. 13, pp. 173–177, 2017.
[3] A. Sodiq, A. A. B. Baloch, S. A. Khan, N. Sezer, S. Mahmoud, M. Jama, and A. Abdelaal, “Towards modern sustainable cities: Review of sustainability principles and trends,” J. Cleaner Prod., vol. 227, pp. 972–1001, Aug. 2019.
[4] S. Cividino, R. Halbac-Cotoara-Zamfir, and L. Salvati, “Revisiting the city life cycle,” Global urbanization and implications for regional development,” Sustainability, vol. 12, no. 5, p. 1151, Feb. 2020.
[5] G. Egidi, L. Salvati, and S. Vinci, “The long way to tipperary: City size and worldwide urban population trends, 1950–2030,” Sustain. Cities Soc., vol. 60, Sep. 2020, Art. no. 102148.

[6] E. Adaku, “Rethinking urban infrastructure cost management in developing countries,” J. Urban Planning Develop., vol. 142, no. 1, Mar. 2016, Art. no. 05014028.

[7] C. Fang, “Important progress and future direction of studies on China’s urban agglomerations,” J. Geog. Graph., Sci., vol. 25, no. 8, pp. 1003–1024, Aug. 2015.

[8] C. Meng, X. Du, Y. Ren, L. Shen, G. Cheng, and J. Wang, “Sustainable urban development: An examination of literature evolution on urban carrying capacity in the Chinese context,” J. Cleaner Prod., vol. 277, Dec. 2020, Art. no. 122902.

[9] Y. L. Zhu and B. Zhang, “The future trend of China’s consumption under the change of demographic structure-analysis based on the data of the seventh national census,” J. Shanxi Normal Univ., Philosophy Social Sci. Ed., vol. 50, pp. 149–162, 2021.

[10] K. Wang and C. H. Lin, “Trend and planning choices after China’s urbanization rate reaches above 60%,” City Planning Rev., vol. 44, pp. 9–17, 2020.

[11] P. Rosasco and L. Sdino, “Infrastructures and sustainability: An estimation model for a new highway near Genoa,” Sustainability, vol. 12, no. 12, p. 5051, Jun. 2020.

[12] V. Balali, K. Yaseri, and Y. Ham, “Algorithmic development of life-cycle assessment: Application of urban water infrastructure systems in Iran,” KSCE J. Civil Eng., vol. 21, no. 5, pp. 1979–1990, Jul. 2017.

[13] H. Wang and Z. Pei, “Urban green corridors analysis for a rapid urbanization city exemplified in Gaoyou City, Jiangsu,” Forests, vol. 11, no. 12, p. 1374, Dec. 2020.

[14] Y. Song and P. Wu, “Earth observation for sustainable infrastructure: A review,” Remote Sens., vol. 13, no. 8, p. 1528, Apr. 2021.

[15] Q. Q. Wang, “The national housing and urban-rural construction working conference held to deploy the ten major tasks in 2019,” Standardization Eng. Construct., vol. 1, pp. 12–17, 2019.

[16] S. Q. Zheng, D. Yu, C. Sun, and G. T. Zhang, “On the allocation of basic educational facilities based on supply-demand matching: A case study of Hefei,” J. East China Normal Univ., Humanities Social Sci., vol. 49, pp. 133–138 and 176, 2017.

[17] S. H. Yan, Y. Li, Q. L. Mao, and S. C. Dong, “The urban municipal infrastructure construction status, problem and countermeasure of China,” Urban Develop. Stud., vol. 19, pp. 28–33, 2012.

[18] D. Hsu, T. C. Lim, and T. Meng, “Rocky steps towards adaptive management and adaptive governance in implementing green infrastructure at urban scale in Philadelphia,” Urban Forestry Urban Greening, vol. 25, Nov. 2020, Art. no. 126791.

[19] M. Meeow, M. Nizamun, and D. Krantz, “Green infrastructure performance in arid and semi-arid urban environments,” Urban Water J., vol. 18, no. 4, pp. 275–285, Apr. 2021.

[20] N. Vasiljević, B. Radić, S. Gavrilović, B. Sljuškić, M. Medarević, and R. Ristić, “The concept of green infrastructure and urban landscape planning: A challenge for urban forestry planning in Belgrade, Serbia,” Forests-Bioeconomy, Forestry, vol. 11, no. 4, pp. 491–498, Aug. 2018.

[21] J. Coutinho-Rodrigues, A. Simão, and C. H. Antunes, “A GIS-based multi-criteria spatial decision support system for planning urban infrastructures,” Decis. Support Syst., vol. 51, no. 3, pp. 720–726, Jun. 2011.

[22] I. R. Bartle, C. J. Bouch, C. J. Baker, and C. D. F. Rogers, “End-user innovation of urban infrastructure: Key factors in the direction of development,” Proc. Inst. Civil Eng.-Municipal Eng., vol. 173, pp. 69–77, 2020.

[23] World Development Report 1994: Infrastructure for Development, Bank World, Washington, DC, USA, 1994.

[24] N. M. Hansen, “Unbalanced growth and regional development,” Econ. Inquiry, vol. 4, pp. 3–14, Oct. 1965.

[25] H. Yee, S. Kim, and S. Kang, “GIS-based evaluation method for accessibility of social infrastructure facilities,” Appl. Sci., vol. 11, no. 12, p. 5581, Jun. 2021.

[26] J. Gossye, “Leisure politics: The construction of social infrastructure and Flemish cultural identity in Belgium, 1950s to 1970s,” J. Urban Hist., vol. 47, no. 3, pp. 526–548, May 2021.

[27] S. Klug and Y. Hayashi, “Urban sprawl and local infrastructure in Japan and Germany,” J. Infrastruct. Syst., vol. 18, no. 4, pp. 232–241, Dec. 2012.

[28] D. W. Fu, “Japan and other countries use private funds to invest in infrastructure,” World Economy Stud., vol. 4, pp. 14–23 and 26, 1994.

[29] D. Wang, “Financial system of infrastructure construction in Japan,” Urban Planning Int., vol. 2, pp. 27–29 and 48, 2001.
[52] V. Palevičius, M. Burinskienė, J. Antuchevičienė, and J. Šaparauskas, “Comparative study of urban area growth: Determining the key criteria of inner urban development,” Symmetry, vol. 11, no. 3, p. 406, Mar. 2019.

[53] M. Jain and A. Korzhenevych, “Spatial disparities, transport infrastructure, and decentralization policy in the Delhi region,” J. Urban Planning Develop., vol. 143, no. 3, Sep. 2017, Art. no. 05017003.

[54] A. Rehman, Z. Deyuan, A. A. Chандio, and I. Hussain, “An empirical analysis of rural and urban populations’ access to electricity: Evidence from Pakistan,” Energy, Sustainability Soc., vol. 8, no. 1, pp. 1–9, Dec. 2018.

[55] S. Lindley, S. Puulet, K. Yeshitela, S. Cilliers, and C. Shackleton, “Rethinking urban green infrastructure and ecosystem services from the perspective of sub-Saharan African cities,” Landscape Urban Planning, vol. 180, pp. 328–338, Dec. 2018.

[56] Y. Yang, J. Liu, and Y. Zhang, “An analysis of the implications of China’s urbanization policy for economic growth and energy consumption,” J. Cleaner Prod., vol. 161, pp. 1251–1262, Sep. 2017.

[57] W. D. Zhang and D. Q. Shi, “Influence on urbanization level by infrastructural construction,” Urban Problems, vol. 11, pp. 31–37, 2015.

[58] P. C. Xiang and Y. Y. Cao, “Research on the matching degree between the urban infrastructure supply and urban population: A case study of Chongqing municipality,” Population Develop., vol. 22, pp. 33–38, 2016.

[59] Y. H. Zou, “Matching between population and public infrastructure under the comprehensive two child policy—A case study of Chengdu, Sichuan Province,” World Surv. Res., vol. 1, pp. 43–46, 2018.

[60] J. Wang, Y. Ren, L. Shen, Z. Liu, Y. Wu, and F. Shi, “A novel evaluation method for urban infrastructures carrying capacity,” Cities, vol. 105, Oct. 2020, Art. no. 102846.

[61] J. Wang, L. Shen, Y. Ren, X. Wei, Y. Tan, and T. Shu, “An alternative model for evaluating the balance of carrying capacity between functional urban infrastructures,” Environ. Impact Assessment Rev., vol. 79, Nov. 2019, Art. no. 106304.

[62] A. O. Hirschman, Shifting Involvements: Private Interest and Public Action. Princeton, NJ, USA: Princeton Univ. Press, 1982, p. 138.

[63] Y. Lin, “New structural economics: Reconstructing the framework of development economics,” China Econ. Quart., vol. 10, no. 1, pp. 1–32, 2010.

[64] S. B. Nielsen and M. Elle, “Assessing the potential for change in urban infrastructure systems,” Environ. Impact Assessment Rev., vol. 20, no. 3, pp. 403–412, Jun. 2000.

[65] Y. Wei, C. Huang, J. Li, and L. Xie, “An evaluation model for urban carrying capacity: A case study of China’s mega-cities,” Habitat Int., vol. 53, pp. 87–96, Apr. 2016.

[66] Y. Wei, C. Huang, P. Lam, Y. Sha, and Y. Feng, “Using urban-carrying capacity as a benchmark for sustainable urban development: An empirical study of Beijing,” Sustainability, vol. 7, no. 3, pp. 3244–3268, Mar. 2015.

[67] Y. Tian and C. Sun, “A spatial differentiation study on comprehensive carrying capacity of the urban agglomeration in the Yangtze river economic belt,” Regional Sci. Urban Econ., vol. 68, pp. 11–22, Jan. 2018.

[68] Y. Cui and Y. Sun, “Social benefit of urban infrastructure: An empirical analysis of four Chinese autonomous municipalities,” Utilities Policy, vol. 58, pp. 16–26, Jun. 2019.

[69] J. Xie, Y. Qin, X. Meng, J. Xu, and L. Wang, “Notice of retraction: The fuzzy comprehensive evaluation of the highway emergency plan based on G1 method,” in Proc. 3rd Int. Conf. Comput. Sci. Inf. Technol., Chengdu, China, Jul. 2010, pp. 313–316.

[70] H. Zhao, Y. Wang, and X. Liu, “The evaluation of smart city construction readiness in China using CRITIC-G1 method and the Bonferroni operation,” IEEE Access, vol. 9, pp. 70024–70038, 2021.

[71] J. Zhao and L. Chai, “A novel approach for urbanization level evaluation based on information entropy principle: A case of Beijing,” Phys. A, Stat. Mech. Appl., vol. 430, pp. 114–125, Jul. 2015.

[72] M. Chen, D. Lu, and L. Zha, “The comprehensive evaluation of China’s urbanization and effects on resources and environment,” J. Geograph. Sci., vol. 20, no. 1, pp. 17–30, Feb. 2010.

[73] Y. Zhang, Z. Su, G. Li, Y. Zhao, and Z. Xu, “Spatial-temporal evolution of sustainable urbanization development: A perspective of the coupling coordination development based on population, industry, and built-up land spatial agglomeration,” Sustainability, vol. 10, no. 6, p. 1766, May 2018.

[74] L. Ding, W. Zhao, Y. Huang, S. Cheng, and C. Liu, “Research on the coupling coordination relationship between urbanization and the air environment: A case study of the area of Wuhan,” Atmosphere, vol. 6, no. 10, pp. 1539–1558, Oct. 2015.

[75] Y. Shi, Q. Zhu, L. Xu, Z. Lu, Y. Wu, X. Wang, Y. Fei, and J. Deng, “Independent or influential? Spatial-temporal features of coordination level between urbanization quality and urbanization scale in China and its driving mechanism,” Int. J. Environ. Res. Public Health, vol. 17, no. 5, p. 1587, Mar. 2020.

[76] C. Yang, W. Zeng, and X. Yang, “Coupling coordination evaluation and sustainable development pattern of geo-ecological environment and urbanization in Chongqing municipality, China,” Sustain. Cities Soc., vol. 61, Oct. 2020, Art. no. 102271.

[77] K. C. Liao, M. Y. Yue, S. W. Sun, H. B. Xue, W. Liu, S. B. Tsai, and J. T. Wang, “An evaluation of coupling coordination between tourism and finance,” Sustainability, vol. 10, no. 7, p. 2320, 2018.

CHENG LU was born in Zibo, Shandong, China, in 1996. He received the bachelor’s degree in engineering from Liaocheng University, in 2019. He is currently pursuing the master’s degree with Qingdao University of Technology. He is mainly engaged in the work of urban development and coupled coordination model.

WENXIA HONG received the master’s degree from Zhejiang University. She is currently a Professor with the Engineering Management Department, Qingdao University of Technology, China. She is mainly engaged in city information modeling (CIM) and risk management.

YETING WANG was born in Linyi, Shandong, China, in 1997. She received the bachelor’s degree in engineering from Yantai University, in 2019. She is currently pursuing the master’s degree with Qingdao University of Technology. She is mainly engaged in the work of smart city construction/evaluation and genetic algorithm.

DEFENG ZHAO was born in Binzhou, Shandong, China, in 1997. She received the bachelor’s degree in management from Liaocheng University, in 2019. She is currently pursuing the master’s degree with Qingdao University of Technology. She is mainly engaged in the work of metro construction risk.