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Measuring coupling coordination between urban economic development and air quality based on the Fuzzy BWM and improved CCD model

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Abstract: Rapid industrialization and urbanization stimulate the fast-growth of the urban economy and generate large numbers of wastes and pollutants, which greatly affect environmental quality. In turn, the strict environmental regulation may negatively affect economic development. Thus, the coordination between economic development and environmental quality has been a thorny problem for policymakers around the world, especially for developing countries such as China. This paper provides a framework for measuring the coupling coordination between urban economic development and air quality for sustainable development. Firstly, it establishes the criteria for measuring urban economic development and air quality, and employs the Fuzzy Best-Worst Method to derive the criteria weights. Then, the performance of urban economic development and air quality can be evaluated. Further, it uses an improved Coupling Coordination Degree model by introducing dynamic contribution coefficients to evaluate the coupling coordination between economic development and air quality. It also conducts a case study by taking the 18 cities in Henan Province of China as examples to perform this framework. After that, it discusses the effectiveness of the Fuzzy Best-Worst Method by comparing with the Fuzzy Analytic Hierarchy Process, and conducts a sensitivity analysis on the contribution coefficients of the improved Coupling Coordination Degree model. Finally, it provides some policy implications for the improvement of coordination between urban economic development and air quality and draws some conclusions.

Keywords: Economic development; Air quality; Fuzzy Best-Worst Method; Coupling coordination degree

1. Introduction

China has experienced rapid industrialization and urbanization with the industrial added value growing more than 56 times and the urbanization level increasing from 17.96% to 60% during 1978—2018. However, several unsustainable issues have also been brought about, such as huge regional economic disparities (Sun et al., 2019a), increasing external resource dependence (Li et al., 2019), and low economic efficiency (Wang et al., 2019a). Especially that the deteriorating air quality has posed great challenges to China's sustainable transition (Lu et al., 2017a; Sun et al., 2019b) and affected the improvement of human health and life quality (Li and Tilt, 2018; Gu et al., 2019). With increasing pressure from urbanization and sustainable transition, most cities confront the dual challenges of economic development and environmental sustainability, which have shown great contradiction with each other during the past several decades of development (Wang et al., 2018). Therefore, the coordination between economic development and air quality has become a critical issue to achieve the sustainable transition in China.

Coordination refers to the mutual reinforcement of two or more systems, and can be used to describe the sustainable development of the interaction between economic growth and environmental protection (Fang et al., 2016; Sun et al., 2018). Air quality is not simply linear-correlated with economic development. Instead, complex nonlinear relationships exist between them (Liu et al., 2007a; Huo and Chai, 2008; Sun et al., 2018). Thus, coupling was introduced to understand and measure this coordination relationship (Solymar et al., 1997; Liu et al., 2002). The coupling relationship between economic development and environment quality is manifested in two aspects. On the one hand, the early economic activities can generate large numbers of pollutants, which result in serious environmental problems and greatly affect the life quality of city dwellers. On the other hand, with economic development and air quality deterioration, the industrial factors also change accordingly, and the industrial structure and distribution undergo optimization and agglomeration. In this way, economy and environment interact with each other, triggering the regular changes in internal structure, which is thought of as a coupling coordination mechanism (Sun et al., 2018; Fan et al., 2019).

Although intensive studies have investigated the relationships among economy, society and environment, it still needs to further discuss the coordination between economic development and air quality, especially the criteria selection and weight derivation for their performance determination. Although the Coupling Coordination Degree (CCD) model was widely used to investigate the coordination between different systems, it’s criticized for subjectivity and arbitrary. To analyze the nexus between economy development and air quality for sustainable development and promote economically growing and environmentally sustainable cities, this study tries to establish a framework which can help evaluate the performance of economic development and air quality in different cities, explore the coupling coordination mechanism between economy and air quality, and provide some policy implications for achieving sustainable management of cities and society.

The rest of this article is organized as follows. Section 2 reviewed the literature on coordination between social economy and ecological environment and highlighted the research gaps as well as the contributions of this study. Section 3 described the framework for measuring the coupling coordination between economic development and air quality. A case study of coupling coordination measurement in 18 provincial cities in Henan Province of China was conducted in Section 4. The discussions on this framework for measuring coupling coordination was presented in Section 5. Section 6 provided some policy implications, and Section 7 drew some conclusions for this study.

2. Literature review

With the increasing concern on sustainable development, many researches have been undertaken to explore the interactions and coupling coordination between different subsystems of social-economic development and ecological environment. By focusing on “social economy- ecological environment”, a variety of related studies were conducted, as presented in Table 1. With the intensive worldwide promotion of urbanization, especially in the developing countries, the coordination development between urbanization and the ecological environment has become a hot topic. Apparently, the coordination between economic, social and environmental systems have become a major topic in related researches, but air quality, a very important element in modern cities, has seldomly been concerned with. In addition, the criteria for measuring economic development simply focus on economic growth but neglect the quality and configuration aspects, which failed to comprehensively reflect the contents and characteristics of economic development.

Table 1. A summary of interactions and coordination between different subsystems.

Research objects	References
Social economy-ecological environment	Sun et al., 2018; Fan et al., 2019; Lu et al., 2017b; Cui et al., 2019a; Wang et al., 2019b; Shi et al., 2020
Economy-society-environment	Yu and Yin, 2018; Cheng et al., 2019
Resources-environment	Wang et al., 2017
Social economy-carbon emission	Shen et al., 2018
Natural resources-financial development-ecological efficiency	Zameer et al., 2020
Tourism-environment	Tang, 2015; Geng et al., 2020
Tourism-economy-environment”	Yuan et al., 2014
Tourism-finance	Liao et al., 2018
Production-living-ecology	Zhou et al., 2016
Land use-ecological security	Cen et al., 2015; Chai et al., 2017
Water efficiency-economic development	Xu et al., 2020
Urbanization-ecological environment	Li et al., 2012; Wang et al., 2014; Wang 2014; Guo et al., 2015; Ai et al., 2016; Fang et al., 2016; Zhao et

	al., 2016; He et al., 2017; Liu et al., 2018a; Zhao et al., 2017; Wang et al., 2019c; Yao et al., 2019; Ariken et al., 2020; Lin et al., 2020
Urbanization-air environment	Ding et al., 2015; Liu et al., 2018b
Urbanization-water ecosystem	Han et al., 2019
Urbanization-ecosystem service value	Xiao et al., 2020
Urbanization-low carbon development	Song et al., 2018
Urbanization-resources-environment	Cui et al., 2019b
Urbanization-population-industry integration	Gan et al., 2020

To measure the coordination between economic and environmental systems, many methods and models were developed and performed. Environment Kuznets Curve was widely used to explain the relationship between economic development and ecological environment, and believed an inverted U-shape relationship existed between them (Grossman and Krueger, 1994). However, due to the temporal and spatial divergence in natural condition, economy, industry, technology, and policies, this curve has also been witnessed as U-shape, N-shape, inverted N-shape, inverted S-shape, and monotonically increasing or decreasing, even irregular shape (Yan et al, 2014; Wang et al., 2016), which led to challenges on the effectiveness, applicability and generality of this hypothesis (Al-Mulali et al., 2015; Liddle, 2015; Dogan and Turkekul, 2016). IPAT model is typically used to analyze the impact of factors such as population, economy, and technology on environment. However, it assumed equal importance for each factor, which is not always this case (Roca, 2002). Thus, the STIRPAT model was introduced to give different weights to these factors by decomposing them, which, however, makes the model more complex and incomprehensible (Shen et al., 2018). There are also some other models such as distance coordination degree model (Tang et al., 2010), pressure-state-response or drive-pressure-state-impact-response model (Yuan et al., 2014; Wang et al., 2019d), systematic dynamics model (Liu, 2011; Xing et al., 2019), grey relational analysis (Zhang et al., 2008; Li et al., 2010), improved matter element extension method (Xu et al., 2016), harmonious regulation model (Luo and Zuo, 2019), and Multiplicative Environmental Data Envelopment Analysis (Han et al., 2020).

Despite that, the CCD model seems to be more preferable in measuring coordination development between different systems. For instance, Cui et al. (2019a) investigated the coupling coordination between social economy and water environment in Kunming, China. Shi et al. (2010) evaluated the coupling coordination degree between economic development and ecological environment in tropical and subtropical regions of China. Shen et al. (2018) assessed the coordination between socio-economy and carbon emission of 30 provinces in China during 1995-2005. Yao et al. (2019) and Lin et al. (2020) explored the coordination between urbanization and eco-environment in China and the west Taiwan Strait urban agglomeration, respectively. However, the traditional CCD model usually assigned equal weights for the contribution of subsystems to the coordination degree subjectively (Wang et al., 2014). This subjectivity in contribution allocation may affect the effectiveness and accuracy of the coordination degree and provide distorting results to policymakers (Li et al.; 2012; He et al., 2017).

As mentioned above, plenty of studies have explored the interactions and coordination between different systems with various methods. However, some research gaps still need to be further discussed:

- The existing interaction and coordination studies focus on social economy and ecological environment, and seldom concerns air quality. The criteria for measuring economic development and air quality are also relatively simple, and couldn’t reflect the multidimensional nature of the systems.
- It lacks an accurate and precise incorporation of the criteria weights because both economic development and air quality are complex social problems, which are of

great uncertainty and ambiguity. Although Fuzzy Analytic Hierarchy Process (AHP) can deal with that, it needs many pairwise comparisons and may lead to inconsistency.

- The CCD model is an efficient tool for analyzing interactions and relationships between different systems, but the traditional CCD model allocates constant contribution coefficients to the subsystems, which leads to arbitrariness, subjectivity and the lack of dynamic changes with economic development and air quality.

To solve the above problems, we provided a framework for measuring the coupling coordination between urban economic development and air quality. The possible contributions of this study are as follows:

- It defines the criteria for evaluating economic development and air quality based on a literature study and theoretical analysis from an all-around perspective.
- It determines the criteria weights of economic development and air quality with the Fuzzy Best-Worst Method (BWM) for measuring their performance.
- By introducing an improved CCD model, it measures and analyzes the coupling coordination between economic development and air quality.

3. Methods

To conduct coupling coordination analysis for urban economic development and environment quality, we established a framework including criteria selection, weight derivation, performance determination, and coordination calculation, as shown in Figure 1. Firstly, it defined these two subsystems by selecting two groups of criteria, and used the Fuzzy BWM to determine the criteria weights. Then, the performance of the two sub-systems can be derived. Finally, it employed an improved CCD model to measure the coupling coordination performance between different subsystems.

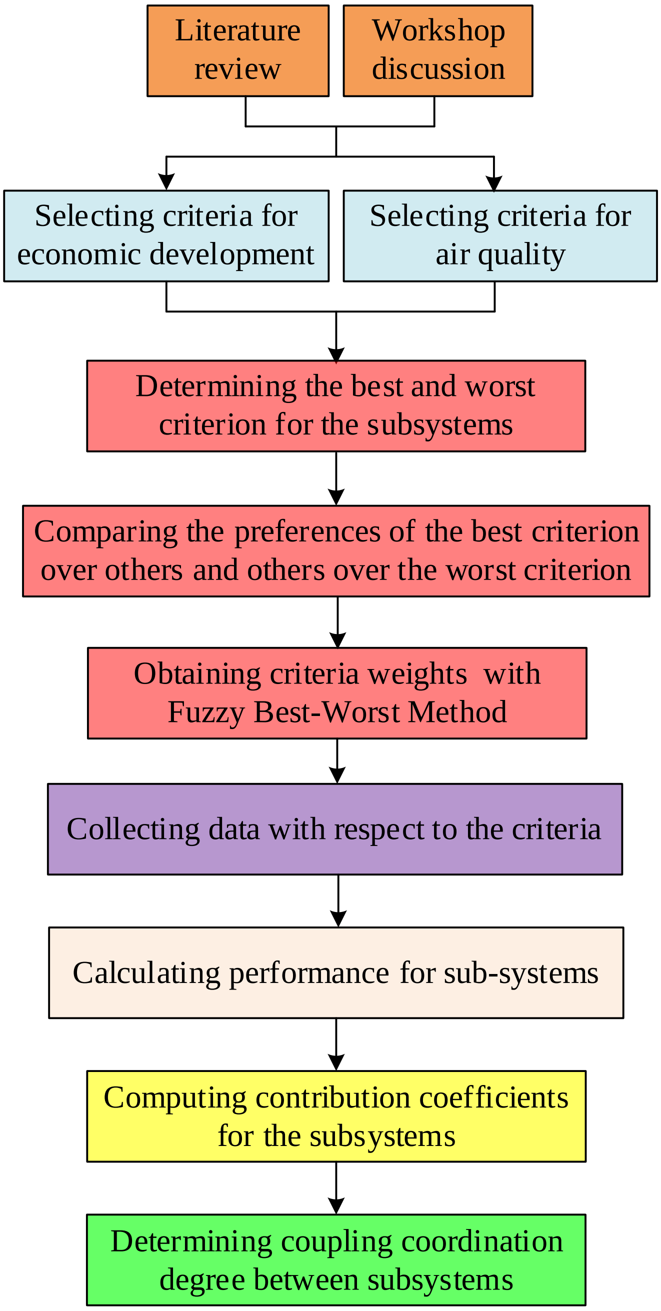


Figure 1. Framework for measuring coupling coordination between urban economic development and air quality.

3.1 Criteria Selection

Criteria selection is the prerequisite to evaluate the performance of economic development and air quality. To do that, we first reviewed a lot of literatures and summarized the alternative criteria. Then a focus group is formed with its members from the fields of industrial engineering, economics, and management to select the appropriate criteria. Finally, four criteria are used to measure economic development, and seven criteria are selected to measure air quality, as shown in Table 2.

Table 2. Components and criteria for urban economic development and air quality.

Variables	Components	Criteria	Unit
Urban economic development	Economic growth	C_1: GDP per capital	10000 CNY per capita
	Industrial structure	C_2: Rationality of industrial structure	/
		C_3: Optimization of industrial structure	/
	Industrial agglomeration	C_4: Local entropy of industrial agglomeration	/
Urban air quality	Air quality pressure	C_5: Energy intensity	Tons SCE /10000 CNY
		C_6: Possession of private passenger cars per capita	Unit/10000 persons
	Air quality state	C_7: Industrial SO_2 emissions per capita	Tons /10000 persons
		C_8: Industrial dust emissions per capita	Tons /10000 persons
	Air quality response	C_9: Proportion of expenditure on environmental protection in total local fiscal expenditure	%
		C_{10}: Green coverage rate in build-up urban area	%
		C_{11}: Annual usage of public transportation per capita	Times per capita

3.1.1. Criteria for urban economic development

Economic development performance measures the economic achievement of the human productive activity. Traditionally, it’s represented by Gross Domestic Product (GDP), which, however, only reflects the quantitative results of economic growth and can’t reveal the qualitative dimensions of economic development (Szreter et al., 2019). In this study, we broke it down into three components: economic growth, industrial structure, and industrial agglomeration. Economic growth was measured by GDP per capita (C_1) (Sun et al., 2018; Fan et al., 2019), industrial structure was measured by considering rationalization (C_2) and optimization (C_3) (Gan et al., 2011), and the agglomeration of the secondary industry (C_4) is used to indicate industrial agglomeration (Shao et al., 2017). The specific criteria are shown in Table 2.

C_1: GDP per capital

GDP per capita is a frequently used criterion and measures the quantitative dimension of economic growth (Fan et al., 2019).

C_2: Rationalization of industrial structure

Rationalization reflects the coordination among different economic sectors and efficiency of resources utilization, and measures the quality of industrial structure. Gan et al. (2011) redefined the Theil Index (Theil, 1967) to measure the rationalization of industrial structure by Eq. (1).

$$ISR=\sum_{k=1}^{3}\left(\frac{GDP_k}{GDP}\right)\ln\left(\frac{GDP_k}{L_k}\Big/\frac{GDP}{L}\right) \tag{1}$$

where L represents total employment, and $k=1,2,3$, indicating the primary, secondary, and tertiary industry, respectively. In a completely balanced economy, ISR equals 0. While, the greater ISR value indicates a more unbalanced and irrational industrial structure.

C_3: Optimization of industrial structure

The optimization of industrial structure is traditionally measured by the share of output value from non-agricultural sectors. However, as the tertiary industry grows much faster than the secondary industry, the ratio of output value of the tertiary industry to that of the secondary industry was calculated to measure the optimization of industrial structure (Gan et al., 2011).

C_4: Local entropy of industrial agglomeration

To measure industrial agglomeration, local entropy is a commonly used criterion, as displayed by Eq. (2). As the industrial sector is the major source of various air pollutants, we mainly focus on agglomeration of the industrial sector (Shao et al., 2017).

$$IA = \frac{L_{ik} \Big/ \sum_{i=1}^{n} L_{ik}}{\sum_{k=1}^{r} L_{ik} \Big/ \sum_{i=1}^{m} \sum_{k=1}^{r} L_{ik}} \tag{2}$$

where L_{ik} is the total employment of the *k*-th industry in the *i*-th city. The greater LA value indicates higher agglomeration level.

3.1.2. Criteria for air quality

To select criteria for measuring air quality, we introduced the Pressure—State—Response (PSR) model (Rapport and Friend, 1979; OECD, 1993), which was usually used to assess the health of ecological system. Based on this model, we selected criteria to measure air quality from the aspects of air quality pressure, air quality state, and air quality response. The pressure of air quality mainly comes from atmospheric pollutant emissions caused by the industrial and transport sectors (Wang et al., 2020), so we measured this dimension with two criteria: energy intensity (C_5) (Balsalobre et al., 2015) and procession of private passenger cars per capita (C_6) (Bazrbachi et al., 2017). The state of air quality can be measured by major air pollutants emissions caused by economic activities, including industrial SO_2 emissions (C_7) and industrial dust emissions (C_8) (Sun et al., 2019c). Air quality can be improved by taking some responding measures, including financial supporting on environment protection, implementation of discharging standards of pollutants, advocating public transport, and urban afforestation. Thus, three criteria were selected to measure this component: government expenditure on environmental protection in total local financial expenditure (C_9) (Sun et al., 2018), green coverage rate in build-up urban area (C_{10}) (Sun et al., 2018), and use of public transportation per capita (C_{11}) (Shen et al., 2018).

C_5: Energy intensity

Since most air pollutants are generated from the combustion of fossil fuels, which exerts great pressure on air quality (Luo et al., 2019). Thus, we selected energy intensity as a major pressure.

C_6: Possession of private passenger cars per capita

Automobile contributes a major part to emissions of greenhouse gases and other air pollutants and particulates (Harrison, 2020). So we also considered the transport sector as the pressure of air quality and used the possession of private passenger cars per capita for measurement.

C_7: Industrial SO_2 emissions per capita

As a major air pollutant that affects air quality, sulfur dioxide (SO_2) used to greatly affect China's nature environment (Zhao et al., 2019). Thus, we use industrial SO_2 emissions per capita as a criterion representing the status of air quality.

C_8: Industrial dust emissions per capita

Smoke and dust emitted from the industrial sector contain a lot of particulates, which also aggravate air quality (Philip et al., 2017). Hence, we also used industrial dust emissions per capita to indicate the status of air quality.

C_9: Proportion of expenditure on environmental protection in total local fiscal expenditure

To improve air quality, the government has to arrange more fiscal budgets on environmental protection, which reflects the importance of environmental protection in local government affairs (He et al., 2018).

C_{10}: Green coverage rate in build-up urban areas

Public green space plays an important role in improving urban air quality (Moradpour and Hosseini, 2020). So, we took it as a response to the deteriorating air quality and measured it with the green coverage rate in build-up urban areas.

C_{11}: Annual usage of public transportation per capita

Considered that the transport sector is an important emitter of air pollutants and particulates

(Chen et al., 2020), we took public transportation as a response to air pollutants and emissions.

Among the eleven selected criteria, six are positively oriented (C_1, C_3, C_4, C_9, C_{10} and C_{11}) and five are negatively oriented (C_2, C_5, C_6, C_7 and C_8). For the positively oriented criteria, the greater value represents better performance. While, for the negatively oriented criteria, the smaller value represents better performance.

3.2. Fuzzy Best-Worst Method

With the criteria for these two sub-systems determined, we need to derive their weights successively. In fact, there are various methods that can determine criteria weights, and the techniques that based on AHP is the most commonly used. However, AHP requires many pairwise comparisons on the relative importance of the criteria and usually encounters inconsistencies in decision making. So, Rezaei (2015) proposed a novel weighting method, namely BWM, which requires less pairwise comparisons and results in better consistency. Because the human qualitative judgments usually contain some degree of ambiguity and uncertainty (Guo and Zhao, 2017). Thus, based on the work of Rezaei (2015), fuzzy numbers can be introduced to execute the pairwise comparisons, which may be more suitable for uncertain and vague issues (Guo and Zhao, 2017). So, we use Fuzzy BWM to derive the criteria weights and then calculate the performance of the sub-systems.

Fuzzy set theory was proposed by Zadeh, and can help solve problems with uncertainty. A fuzzy set $\tilde{a}$ is a pair (U,m), where U is a set, and $m:U\rightarrow[0,1]$ is the membership function $\mu_{\tilde{a}}(x)$, associating with each element x in a universe of discourse X by a real number in the interval $[0,1]$.

A triangular fuzzy number $\tilde{a}=(l,m,u)$ is defined if the membership function is as follows:

$$\mu_{\tilde{a}}(x)=\begin{cases} 0 & x<l \\ \dfrac{x-l}{m-l} & l\le x<m \\ \dfrac{u-x}{u-m} & m\le x\le u \\ 0 & x>u \end{cases} \tag{3}$$

where l, m and u represent the lower, most possible and upper value of the triangular fuzzy number $\tilde{a}$.

For more operational laws of triangular fuzzy numbers, Ocampo-Duque et al., (2006) and Güngör et al. (2009) can be referred to.

The procedure of Fuzzy BWM is as follows (Guo and Zhao, 2017; Aboutorab et al., 2018):

Step 1: Determine the decision criteria.

Let's assume there are *n* criteria in the decision-making problem $C:\left(c_1,c_2,\cdots,c_n\right)$.

Step 2: Select the most important or best and the least important or worst criteria.

The decision-makers need to identify the best and worst criteria based on the nature and goal of the decision problem, which are donated by C_B and C_W, respectively.

Step 3: Conduct fuzzy comparisons for the best criterion.

The decision-makers need to compare the preferences of the best criterion over all the others by using linguistic terms and then translate them into fuzzy triangular numbers by Table 3. The determined fuzzy Best-to-Others vector is as shown in Eq. (4).

$$\tilde{A}_{BO}=(\tilde{a}_{B1},\tilde{a}_{B2},\cdots,\tilde{a}_{Bn}) \tag{4}$$

where $\tilde{a}_{Bj}$ donates the fuzzy preference of the best criterion C_B over criterion j. It is defined that $\tilde{a}_{BB}$=(1,1,1).

Table 3. Linguistic terms and the corresponding fuzzy triangular numbers (Guo and Zhao, 2017).

Linguistic terms	fuzzy triangular numbers
Equally important (E)	(1,1,1)
Weakly important (W)	(2/3,1,3/2)
Fairly important (F)	(3/2,2,5/2)
Very important (V)	(5/2,3,7/2)
Absolutely important (A)	(7/2,4,9/2)

Step 4: Conduct fuzzy comparisons for the worst criterion.

In this step, the other part of the fuzzy pairwise comparisons is executed. By using the linguistic terms in Table 3, the fuzzy preferences of all the criteria over the worst criterion can be derived and the fuzzy Others-to-Worst vector is as shown in Eq. (5).

$$\tilde{A}_{OW} = (\tilde{a}_{1W}, \tilde{a}_{2W}, \cdots, \tilde{a}_{nW}) \tag{5}$$

where $\tilde{a}_{jW}$ donates the fuzzy preference of criterion j over the worst criterion c_W. It is defined that $\tilde{a}_{WW} = (1,1,1)$.

Step 5: Derive the optimal fuzzy weight vector $W = (\tilde{w}_1, \tilde{w}_2, \cdots, \tilde{w}_n)$.

The fuzzy weight for each criterion can be derived by the following nonlinear program model in Eq. (6) (Guo and Zhao, 2017).

$$\begin{aligned} & \min \tilde{\xi} \\ & s.t. \begin{cases} \left| \dfrac{\tilde{w}_B}{\tilde{w}_j} - \tilde{a}_{Bj} \right| \le \tilde{\xi} \\ \left| \dfrac{\tilde{w}_j}{\tilde{w}_W} - \tilde{a}_{jW} \right| \le \tilde{\xi} \\ \sum_{j=1}^{n} R(\tilde{w}_j) = 1 \\ l_j^W \le m_j^W \le u_j^W \\ l_j^W \ge 0 \\ j = 1, 2, \cdots, n \end{cases} \end{aligned} \tag{6}$$

where $\tilde{w}_B = (l_B^w, m_B^w, u_B^w)$, $\tilde{w}_j = (l_j^w, m_j^w, u_j^w)$, $\tilde{w}_W = (l_W^w, m_W^w, u_W^w)$, $\tilde{a}_{Bj} = (l_{Bj}, m_{Bj}, u_{Bj})$, $\tilde{a}_{jW} = (l_{jW}, m_{jW}, u_{jW})$,

$\tilde{\xi}=\left(l^{\xi},m^{\xi},u^{\xi}\right)$, and $l^{\xi}\le m^{\xi}\le u^{\xi}$. We assume that $\tilde{\xi}^{*}=\left(k^{*},k^{*},k^{*}\right)$ and $k^{*}\le l^{\xi}$.

Then Eq. (6) and be rewritten as Eq. (7) (Guo and Zhao, 2017).

$$\min \tilde{\xi}^{*}$$
$$s.t.\begin{cases}\left|\dfrac{(l_B^w,m_B^w,u_B^w)}{(l_j^w,m_j^w,u_j^w)}-(l_{Bj},m_{Bj},u_{Bj})\right|\le(k^*,k^*,k^*)\\ \left|\dfrac{(l_j^w,m_j^w,u_j^w)}{(l_W^w,m_W^w,u_W^w)}-(l_{jW},m_{jW},u_{jW})\right|\le(k^*,k^*,k^*)\\ \sum_{j=1}^{n}R(\tilde{w}_j)=1\\ l_j^w\le m_j^w\le u_j^w\\ l_j^w\ge 0\\ j=1,2,\cdots,n\end{cases} \tag{7}$$

The optimal fuzzy weight vector $W=(\tilde{w}_1,\tilde{w}_2,\cdots,\tilde{w}_n)$ and $\tilde{\xi}^{*}$ can be derived by solving the programing model in Eq. (7) (Guo and Zhao, 2017).

Step 6: Check the consistency ratio of Fuzzy BWM.

The consistency ratio (CR) can be obtained by Eq. (8) (Guo and Zhao, 2017).

$$CR=\frac{\xi^{*}}{CI} \tag{8}$$

where $CR\in(0,1)$. Usually, when $CR\le 0.1$, it indicates an acceptable consistency. CI is the consistency index, and is determined by the preference comparison of the best criterion over the worst, as shown in Table 4 (Guo and Zhao, 2017).

Table 4. Consistency index for Fuzzy BWM (Guo and Zhao, 2017).

$\tilde{a}_{BW}$	(1,1,1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(7/2, 4, 9/2)
CI	3.00	3.80	5.29	6.69	8.04

Step 7: Transform the optimal fuzzy weights into crisp weights.

If all the fuzzy comparisons are consistent, the fuzzy weights can be transformed to crisp values by Eq. (9) (Liao et al., 2013; Zhao & Guo, 2014).

$$R(\tilde{a}_i)=\frac{l_i+4m_i+u_i}{6} \tag{9}$$

where $R(\tilde{a}_i)$ is the graded mean integration representation of the triangular fuzzy number $\tilde{a}_i=\left(l_i,m_i,u_i\right)$ and indicates the final ranking of criterion i.

3.3. Coupling coordination degree model

There is a complex interaction between economic development and air quality (Liu et al., 2007b; Jiang and Chen, 2020). Rapid industrialization and economic growth may lead to the massive emissions of various air pollutants and particulates, which is the main cause of air quality deterioration. To improve air quality, the governments implement various policies to intervene and adjust economic activities, which in turn promotes the improvement of environmental quality (He et al.., 2018). This interaction between economic development and air quality requires a model to analyze the mutual effects between two elements or systems.

CCD model is an efficient tool for analyzing the relationship between economic development and environmental quality by relying on the coupling degree and the coordination degree. Coupling degree refers to the interactive influence between two or more systems to achieve a dynamic and coordinated development, which reflects the degree of mutual dependence and mutual restriction between systems (Tang et al., 2017). Coordination degree refers to the degree of benign coupling in the coupling interaction relationship, which reflects the quality of coordination (Huang et al., 2021). Coupling coordination measures the positive interaction, harmonious and consistent development of various elements or systems (Fang et al., 2016; Sun et al., 2018; Fan et al., 2019). However, the traditional CCD model is usually criticized for the subjective and equal weights of contributions of the elements or subsystems

(Li et al., 2012; Wang et al., 2014; He et al., 2017). Thus, we described an improved CCD model by introducing dynamic and objective weights of contributions to subsystems in this section.

3.3.1. Traditional CCD model

The procedure of traditional CCD model is presented as follows (Fan et al., 2019):

Step 1: Normalize the data for each criterion. As the data for different criteria varies in terms of magnitude and measurement, the positively and negatively oriented criteria need to be normalized with the extreme value method by following Eq. (10) and (11), respectively.

$$a_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \tag{10}$$

$$a_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \tag{11}$$

where x_{ij} is the actual value of criterion j for object i, a_{ij} is the normalized value, $\max x_j$ and $\min x_j$ are the maximum and minimum value for criterion j, respectively. $i = 1, 2, \cdots, m$, and $j = 1, 2, \cdots, n$.

Step 2: Calculate the synthetic value as performance for each subsystem. To do that, ω_j, the weight for criterion j, needs to be determined, then the synthetic value for the subsystem can be calculated by Eq. (12).

$$u_i = \sum_{j=1}^{n} a_{ij} \omega_j \tag{12}$$

Step 3: Obtain the coupling degree. The coupling degree between different subsystems can be derived by Eq. (13) (Cong, 2019).

$$C = k \times \left[\frac{u_1 \times u_2 \times \cdots \times u_k}{(u_1 + u_2 + \cdots + u_k)^k} \right]^{1/k} \tag{13}$$

where C is the coupling degree, k donates the number of subsystems, and u_i is performance of subsystem i.

In our study, there are two subsystems, namely economic development and air quality.

Step 4: Calculate the coupling coordination degree by Eq. (14) and (15).

$$T = \alpha u_1 + \beta u_2 + \cdots + \delta u_k \tag{14}$$

$$D = \sqrt{C \times T} \tag{15}$$

where T is the comprehensive development index that measures the overall effect of the subsystems. $\alpha, \beta, \cdots, \delta$ represent the weights of contribution of the subsystems, and $\alpha + \beta + \cdots + \delta = 1$. Traditionally, all sub-systems share equal weights. D refers to the coupling coordination degree.

3.3.2. Improved coupling coordination degree model

Traditionally, the contribution coefficients of $\alpha, \beta, \cdots, \delta$ in Eq. (14), which represent the weights of the subsystems, were determined subjectively, and equal weight of contribution were usually allocated to each subsystem. However, this practice is often criticized, so some other approaches were proposed (Shen et al., 2018). The coupling coordination reveals the dynamic development mechanism between subsystems from low level to high level (Haken, 1983). A higher level of coordination can be achieved through a strong coupling status between subsystems. To achieve that, a small gap should be kept between the performance of the subsystems (Braden and Kolstad, 1991). There are two approaches to reduce this gap and improve the coupling coordination degree between the subsystems, either improving the less developed subsystem or aggravating the better developed one. Apparently, improving the less developed subsystem is a more preferable choice, which means more attention and efforts should be allocated to this subsystem. Thus, the subsystem with worse performance should be given a higher weight to indicate its importance and attract more social attention, promote the development of the laggard subsystem and reduce the gaps between them. The greater the gap is, the greater weight value should be allocated to the less developed subsystem. When this gap has been narrowed, its weight should also be reduced accordingly, until these subsystems obtained equal performance. In this way, the subsystems promote the development with each other and move towards better coordination (Shen et al., 2018). According to this analysis, the relationship of the contribution coefficients for the two subsystems in this study, urban economic development and air quality, can be expressed by Eq. (16) (Shen et al., 2018).

$$\begin{cases} \alpha + \beta = 1 \\ \alpha > \beta \ \text{ when } u_1 < u_2 \\ \alpha < \beta \ \text{ when } u_1 > u_2 \end{cases} \tag{16}$$

where u_1 and u_2 donate the performance score of urban economic development and air quality, α and β are their contribution coefficients.

The determination of the contribution coefficients can be conducted by Eq. (17) (Shen et al., 2018).

$$\begin{cases} \alpha^* = \dfrac{u_2}{u_1 + u_2} \\ \beta^* = \dfrac{u_1}{u_1 + u_2} \end{cases} \tag{17}$$

where α^* and β^* are the improved contribution or weight coefficients of the two subsystems.

Then, with the improved weight coefficients, the degree of improved coupling coordination between the two subsystems can be derived by Eq. (18) and (19).

$$T = \alpha^* \times u_1 + \beta^* \times u_2 \tag{18}$$

$$D^* = \sqrt{C \times T^*} \tag{19}$$

3.3.3. Types of coupling coordination

To make an accurate judgement on the coupling coordination between urban economic development and air quality, it’s necessary to define the coupling coordination status. Traditionally, this status is defined by coupling coordination degree, and the greater value indicates better coupling coordination. Table 5 describes the discerning definition of the coupling coordination status.

Table 5. Discerning definition of the coupling coordination status (Li et al., 2012).

Coordination types	Degree of coupling coordination	Description
Excellent coordination	$0.8 < D \leq 1$	A highly coordinated relationship between economic development and air quality.
Good coordination	$0.6 < D \leq 0.8$	A relatively strong interaction between economic development and air quality.
Basic coordination	$0.4 < D \leq 0.6$	A moderate coordination relationship between economic development and air quality.
Weak coordination	$0.2 < D \leq 0.4$	There is a relatively weak nexus between economic development and air quality, and economic development.
Poor coordination	$0 \leq D \leq 0.2$	A highly imbalanced relationship between economic development and air quality.

4. Case study

As a typical province in China, Henan Province is located in the central region of this country, downstream of the Yellow River. It ranks 3rd in total permanent population, and 5th both in GDP and energy consumption around the country. As a major economic province, Henan is also an area hardest hit by air pollution. For a long time, due to the extensive economic growth, simple energy structure dominated by coal, and low investment in air pollution control, air pollutants and carbon emissions in Henan Province were much higher than the national average. Due to the divergence in climate and geographical features, economic mode, and industrial structure among different areas in Henan Province, great varieties were shown in air pollutant emissions and the changing tendencies. To demonstrate and test our framework for measuring the coupling coordination between economic development and air quality in urban area, we conduct a case study by investigating the coordination between urban economic development and air quality of the 18 cities in Henan Province of China during the period of 2007—2018.

4.1. Weight determination

The weight of each criterion can be obtained with Fuzzy BWM based on the hierarchy framework in Table 2. According to the procedure of Fuzzy BWM, economic development and air quality are two systems. The best and worst criteria as well as the Best-to-Others and Others-to-Worst vectors for each system need to be determined by expert judgement. So, a focus group was formed by inviting several professors and PhD students from the fields of industrial engineering, economics, and management. Each group member would list his or her opinions on the determination of best and worst criteria as well as the Best-to-Others and Others-to-Worst vectors for both systems, and explain the reasons. After several rounds of discussion, the opinions would be gradually unified. If disagreements still happen, a final decision can be achieved by voting.

As for urban economic development, “GDP per capita” (C_1) and “Local entropy of industrial agglomeration” (C_4) are identified as the best and worst criteria, respectively, based on the linguistic terms (see Table 3) determined by focus group discussion. Then, the preference comparisons of the best criterion over all the criteria, as well as the preference comparisons of the worst criterion over all the criteria can be derived, as shown in Table A1 in Appendix A.

Similarly, “Energy intensity” (C_5) and “Annual usage of public transportation per capita” (C_{11}) are identified as the best and worst criteria for urban air quality, and the comparisons of the best criterion over others and others over the worst has been determined as presented in Table A2 in Appendix A.

Then, according to Table 3, we can derive the fuzzy Best-to-Others vector and Others-to-Worst vector, which is as follows:

$$\tilde{A}_{BO} = [(1,1,1), (3/2, 2, 5/2), (2/3, 1, 3/2), (5/2, 3, 7/2)]$$

$$\tilde{A}_{OW} = [(5/2, 3, 7/2), (3/2, 2, 5/2),\ (2/3, 1, 3/2),\ (1,1,1)]$$

To get the optimal fuzzy weights for all criteria, we can build a nonlinear programing model by Eq. (8) as follows:

$$\min k^*$$
$$s.t.\begin{cases} \left|\dfrac{(l_1^w, m_1^w, u_1^w)}{(l_2^w, m_2^w, u_2^w)} - (l_{12}, m_{12}, u_{12})\right| \le (k^*, k^*, k^*) \\ \left|\dfrac{(l_1^w, m_1^w, u_1^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{13}, m_{13}, u_{13})\right| \le (k^*, k^*, k^*) \\ \left|\dfrac{(l_1^w, m_1^w, u_1^w)}{(l_4^w, m_4^w, u_4^w)} - (l_{14}, m_{14}, u_{14})\right| \le (k^*, k^*, k^*) \\ \left|\dfrac{(l_2^w, m_2^w, u_2^w)}{(l_4^w, m_4^w, u_4^w)} - (l_{24}, m_{24}, u_{24})\right| \le (k^*, k^*, k^*) \\ \left|\dfrac{(l_3^w, m_3^w, u_3^w)}{(l_4^w, m_4^w, u_4^w)} - (l_{34}, m_{34}, u_{34})\right| \le (k^*, k^*, k^*) \\ \sum_{j=1}^{n} R(\tilde{w}_j) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ j = 1, 2, \cdots, n \end{cases} \tag{20}$$

With l_{ij}, m_{ij}, and u_{ij} defined in $\tilde{A}_{BO}$ and $\tilde{A}_{OW}$, the following model can be obtained:

$$\min k^*$$
$$s.t.\begin{cases} -k \le l_1 \ / u_2 - 1.5 \le k \\ -k \le m_1 \ / m_2 - 2 \le k \\ -k \le u_1 \ / l_2 - 2.5 \le k \\ -k \le l_1 \ / u_3 - 0.67 \le k \\ -k \le m_1 \ / m_3 - 1 \le k \\ -k \le u_1 \ / l_3 - 1.5 \le k \\ -k \le l_1 \ / u_4 - 3.5 \le k \\ -k \le m_1 \ / m_4 - 4 \le k \\ -k \le u_1 \ / l_4 - 4.5 \le k \\ -k \le l_2 \ / u_4 - 0.67 \le k \\ -k \le m_2 \ / m_4 - 1 \le k \\ -k \le u_2 \ / l_4 - 1.5 \le k \\ -k \le l_3 \ / u_4 - 1.5 \le k \\ -k \le m_3 \ / m_4 - 2 \le k \\ -k \le u_3 \ / l_4 - 2.5 \le k \\ \frac{1}{6} l_1 + \frac{4}{6} m_1 + \frac{1}{6} u_1 + \frac{1}{6} l_2 + \frac{4}{6} m_2 + \frac{1}{6} u_2 + \\ \frac{1}{6} l_3 + \frac{4}{6} m_3 + \frac{1}{6} u_3 + \frac{1}{6} l_4 + \frac{4}{6} m_4 + \frac{1}{6} u_4 = 1 \\ l_1 \le m_1 \le u_1 \\ l_2 \le m_2 \le u_2 \\ l_3 \le m_3 \le u_3 \\ l_4 \le m_4 \le u_4 \\ k \ge 0 \end{cases} \tag{21}$$

By solving Eq. (21), the optimal fuzzy weights of the four criteria of economic development are as follows:

$\tilde{w}_1^* = (0.4101, 0.4144, 0.4734)$, $\tilde{w}_2^* = (0.1583, 0.1663, 0.2060)$, $\tilde{w}_3^* = (0.2378, 0.2779, 0.3532)$, $\tilde{w}_4^* = (0.1181, 0.1181, 0.1363)$, $\tilde{\xi}^* = (0.4911,\ 0.4911,\ 0.4911)$

Since $a_{BW} = a_{14} = (7/2,\ 4,\ 9/2)$, so the corresponding CI is 8.04 as shown in Table 4. So, we can calculate that $CR = 0.4911/8.04 = 0.0610 < 0.1$, which indicates a very good consistence.

After that, we can obtain the crisp weights for the criteria of economic development by Eq.

(9), which are $w_1^* = 0.4235$, $\tilde{w}_2^* = 0.1716$, $\tilde{w}_3^* = 0.2838$, $\tilde{w}_4^* = 0.1211$.

By taking the same procedure to the fuzzy preference comparisons in Table A2 in Appendix A, we can obtain the optimal fuzzy weights for the criteria of air quality: $\tilde{w}_5^* = (0.2901, 0.2901, 0.2901)$, $\tilde{w}_6^* = (0.1135, 0.1327, 0.1692)$, $\tilde{w}_7^* = (0.0781, 0.0903, 0.1069)$, $\tilde{w}_8^* = (0.1135, 0.1327, 0.1692)$, $\tilde{w}_9^* = (0.1249, 0.1327, 0.1692)$, $\tilde{w}_{10}^* = (0.1135, 0.1327, 0.1692)$, $\tilde{w}_{11}^* = (0.0623, 0.0743, 0.0883)$, $\tilde{\xi}^* = (0.2145, 0.2145, 0.2145)$.

The CR is calculated as $0.2145/8.04 = 0.0267 < 0.1$, which also indicates a very good consistency for the fuzzy preference comparisons. Therefore, the crisp weight with respect the seven criteria of air quality is $w_5^* = 0.2901$, $\tilde{w}_6^* = 0.1356$, $\tilde{w}_7^* = 0.0910$, $\tilde{w}_8^* = 0.1356$, $\tilde{w}_9^* = 0.1375$, $\tilde{w}_{10}^* = 0.1355$, $\tilde{w}_{11}^* = 0.0747$.

4.2. Performance evaluation for sub-systems

The data with respect to the criteria are derived from Henan Statistical Yearbook and China City Statistical Yearbook, and can be normalized by Eq. (10) and (11). With the criteria weights determined by Fuzzy BWM, the performance for the two sub-systems, economic development and air quality, can be calculated by Eq. (12).

The economic development performance for the 18 cities of Henan Province from 2007 to 2018 was calculated as presented in Table B1 in Appendix B and Figure 2. Generally, we can find that the average economic development performance in Henan province shows a significant improvement with the average score increasing from 0.3153 to 0.5844 during this period. Zhengzhou, the capital city of Henan Province, experienced a much better economic development performance than other cities with an average score of 0.6499. It was followed by Luoyang and Jiyuan with an average performance score of 0.5130 and 0.4887, respectively. While, Sanmenxia, Puyang, Luohe, and Pingdingshan experienced the worst economic development performance with annual performance scores of 0.3253, 0.3255, 0.3831, and 0.3465, respectively. Even so, all cities experienced an obvious progress in economic development within this period. Sanmenxia, Puyang, Jiyuan, and Luoyang enjoyed the greatest growth of economic development performance by increasing 150.48%, 144.29%, 132.11%, and 122.76%, respectively. On the contrary, with a growth rate of 37.52%, 47.03%, 47.81%, and 55.78%, respectively, Hebi, Zhoukou, Xinyang, and Zhengzhou demonstrated the slowest growth.

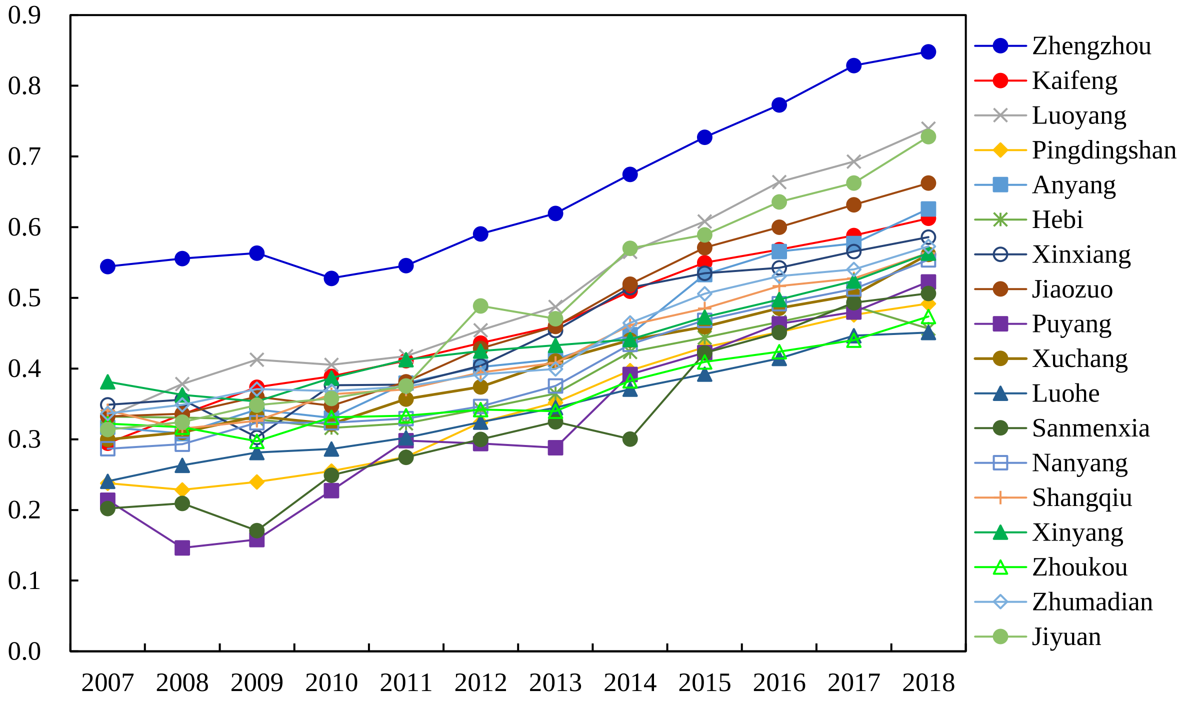


Figure 2. Economic development performance for 18 cities of Henan Province, 2007—2018.

The performance of urban air quality for the 18 cities within the period of 2007—2018 was presented as Table B2 in Appendix B and Figure 3. We noticed that the performance scores vary in the range of 0.37 to 0.80 with an average of 0.6515. Over these twelve years, the annual average performance score increased from 0.5942 to 0.6956, indicating the improving air quality within this period. However, it is not as obvious as the improvement of economic development. Before 2014, the air quality performance has been stagnated and even deteriorating for a while, and an upward tendency was witnessed in the following years, mainly due to the efficient environmental governance. Among the 18 cities, Zhoukou, Luohe, Xinyang, and Zhumadian that located in the southeast of Henan Province have the best air quality performance. By contrast, the northern cities, including Jiyuan, Anyang, Sanmenxia, Jiaozuo, Hebi and Puyang, showed relatively bad air quality performance. Pingdingshan, a city in central Henan Province with a large-scale coal industry, also suffered from terrible air quality performance. Overall speaking, the air quality in Henan Province has improved over this period, however, still slower than the growth of economic development.

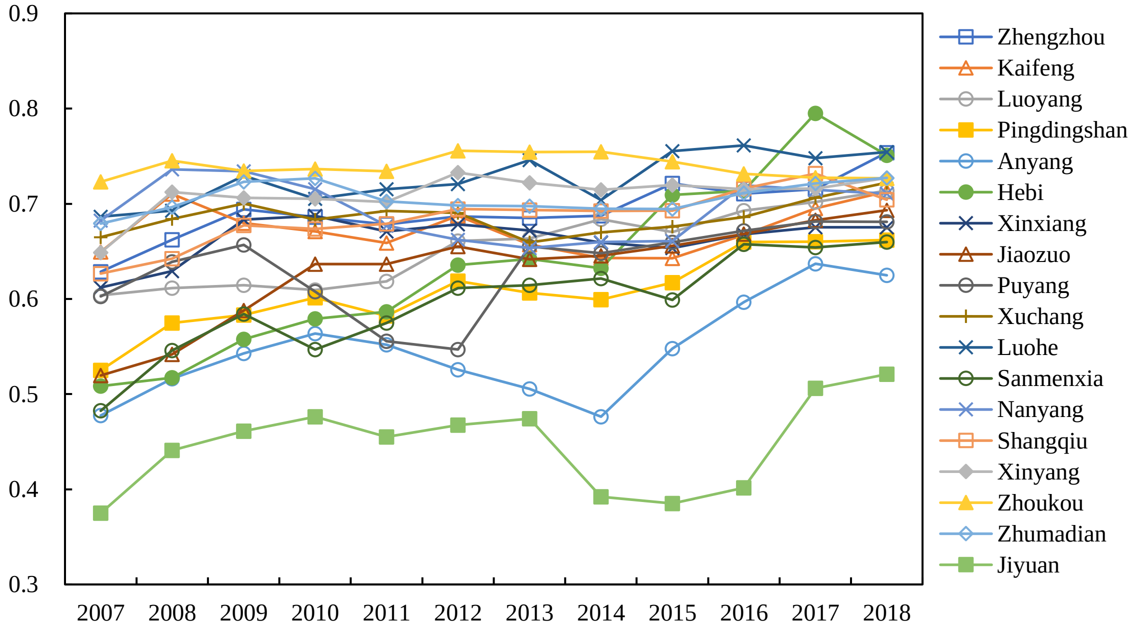


Figure 3. Air quality performance for 18 cities of Henan Province, 2007—2018.

4.3. Coupling coordination degree by improved CCD model

In the improved CCD model, the defined dynamic contribution coefficients, α^* and β^*, can be calculated by Eq. (17) and were presented in Table C1 of Appendix C. By using these dynamic contribution coefficients, the improved CCD value of the 18 cities within the period of 2007—2018 can be derived as shown in Table C2 of Appendix C and Figure 4, from which we can find that all the 18 cities experienced ascending and good coupling coordination performance over this period based on the discerning definition in Table 5. More intuitively, we can calculate the average improved CCD value with respect to each city within this period, as is shown in Figure 5. It indicates that Zhengzhou has the most outstanding CCD value than others, and can be judged as excellent coordination between urban economic development and air quality since 2012. Luoyang and Jiaozuo also achieved excellent coordination from the late 2010s. Although all cities have gotten their CCD value over 0.6, indicating their good coordination, Jiyuan and Sanmenxia are still less coordinated than others.

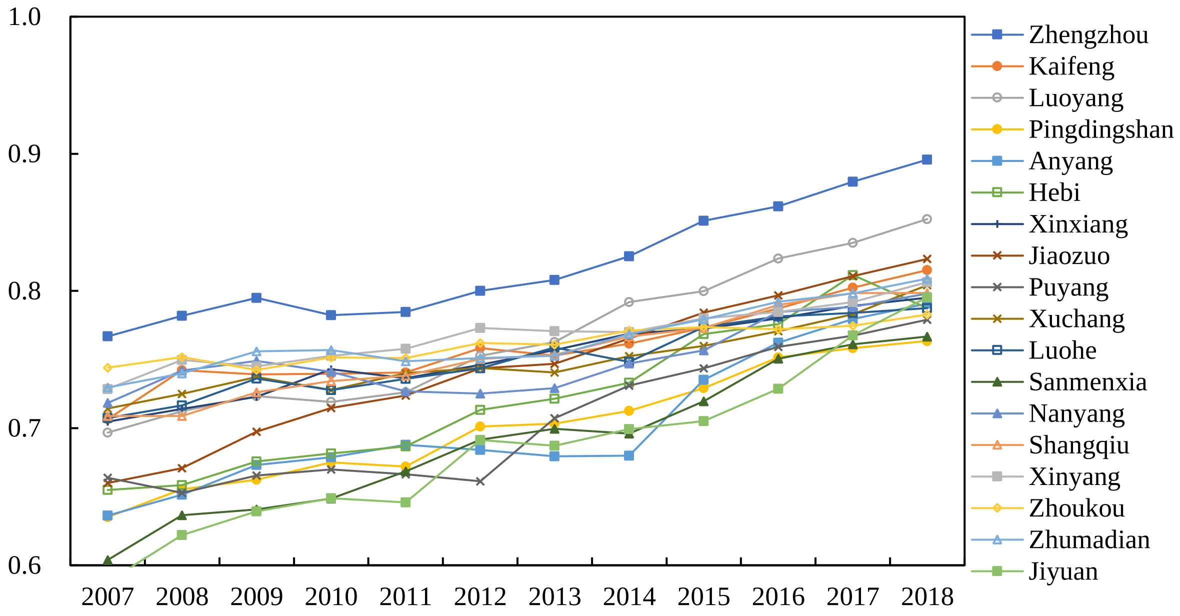


Figure 4. CCD value of the 18 cities in Henan Province derived from improved CCD model, 2007—2018.

Also, we can investigate the changing trends of the coordination situation for each city, which has also been presented in Figure 5. It is noticed that the coordination has been improved greatly over this period with an average growth rate of 17.3% for the coupling coordination degree value, despite their significant divergence among different cities. Among them, Jiyuan, Sanmenxia, Jiaozuo, and Anyang have made the greatest improvement, followed by Luoyang, Pingdingshan, and Hebi. While, Zhoukou has the least improvement of coordination between urban economic development and air quality, followed by some other cities in the south and east, such as Xinyang, Zhumadian, Nanyang, and Luohe.

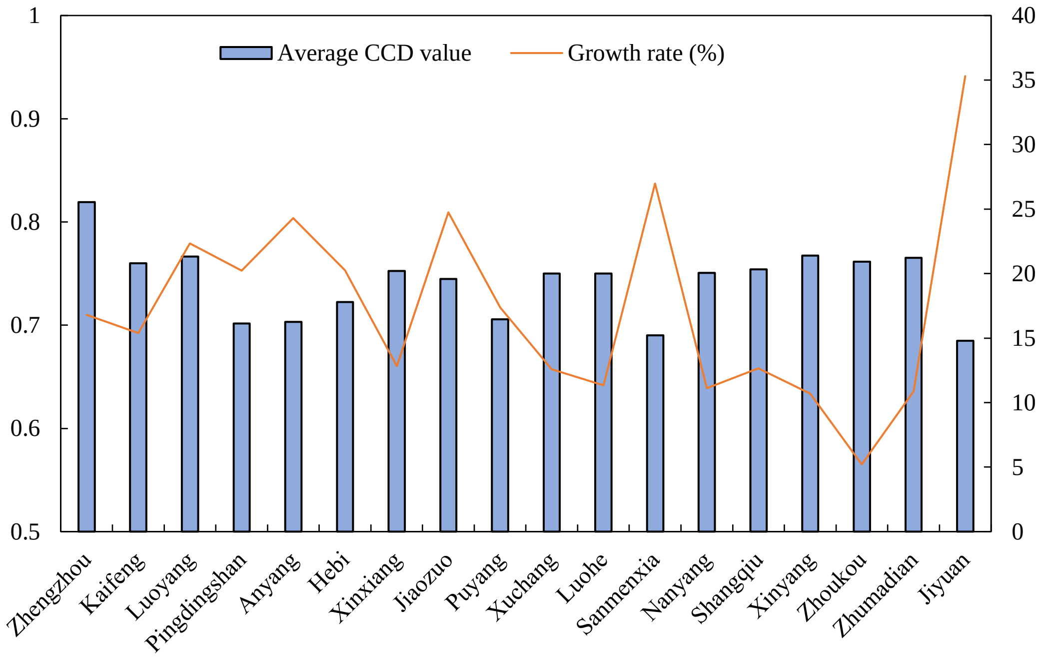


Figure 5. Average improved CCD value and growth rate of the provincial cities in Henan Province.

4.4. Regional analysis of coupling coordination in Henan Province

In terms of economic geography, the 18 cities in Henan Province can be divided into four economic regions: central urban agglomeration zone, north economic zone, west and southwest economic zone, and Huang-Huai economic zone. The central urban agglomeration zone is centered on the capital city, Zhengzhou, and includes another seven cities: Luoyang, Kaifeng, Xinxiang, Jiaozuo, Xuchang, Pingdingshan, Luohe, and Jiyuan. The north economic zone includes three cities: Anyang, Hebi, and Puyang. The west and southwest economic zone covers two cities: Sanmenxia and Nanyang. The Huang-Huai economic zone is located in the southeast part of Henan Province and involves Zhumadian, Shangqiu, Zhoukou, and Xinyang.

By aggregating the city-level improved CCD value into regional-level, we can compare the coordination situation for different economic regions of Henan Province within this period. As shown in Figure 6, it is evident that Huang-Huai economic zone and central urban agglomeration zone shared better coordination between economic development and air quality than the other two regions. We can also notice that the gaps in coordination among the four regions have been narrowed over this period. At the early stage, the Huang-Huai economic zone took the leading position in coordination performance for many years and was finally replaced by the central urban agglomeration zone in 2016. Besides, the leading advantages of the Huang-Huai economic zone over the other two regions were also gradually shrinking.

In fact, great variance was existed in economic output, industrial structure, industrialization, and urbanization among the four economic zones. The central urban agglomeration zone plays the leading role in economic development with complete industrial system, abundant mineral and energy resources, and convenient transportation infrastructure. Thus, this region has the best economic development performance within this period. In terms of air quality, the extensive industrial development model generated large number of industrial wastes and pollutants, resulting in the bad air quality performance. With more attention on environmental protection in the following years, the air quality has gradually been improved, which promoted the improvement of coordination between the two subsystems. The Huang-Huai economic zone is characterized by plain terrain with plentiful water resources, which gives it unique advantages in agriculture and the related industries. Thus, this region has the best environmental quality and relatively slow economic development. So, it has the best coordination performance before 2015, which, however, was negatively affected by the relatively slow of economic growth in the following years. The other two regions cover the north, west and southwest economic zones, are gifted with abundant coal and mineral resources. Consequently, the large scales of coal and mineral industries leaded to serious ecological destruction and produced a lot of environmental pollutants, resulting the imbalance between local economic development and air quality.

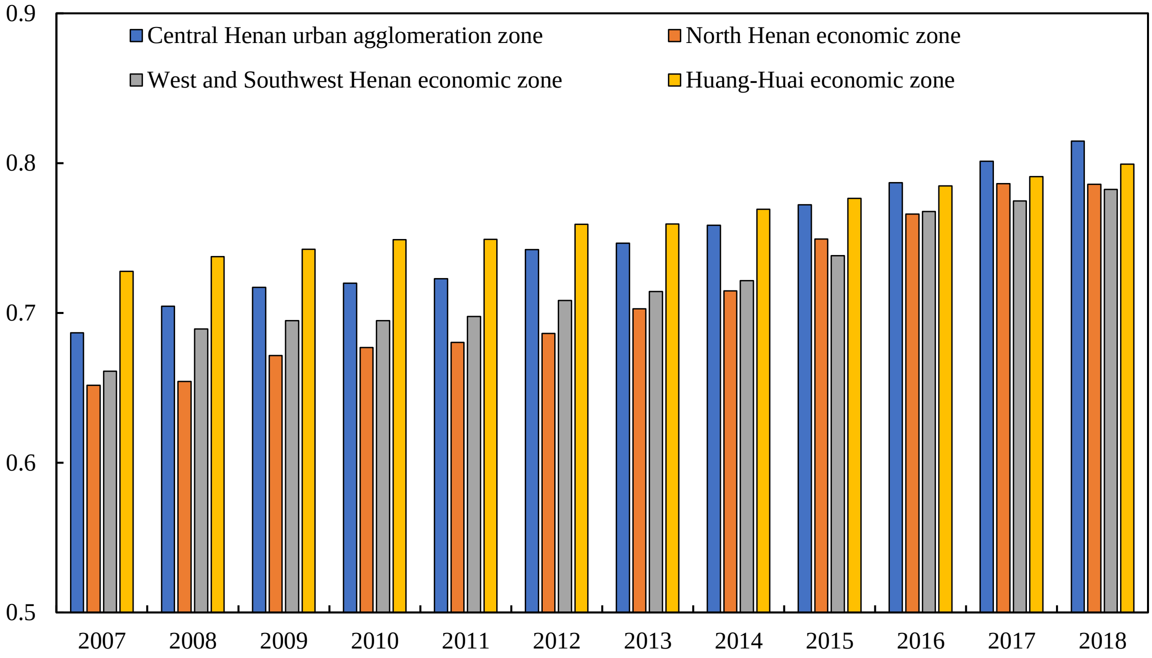


Figure 6. Average improved CCD value for the four economic zones of Henan Province.

5. Discussions

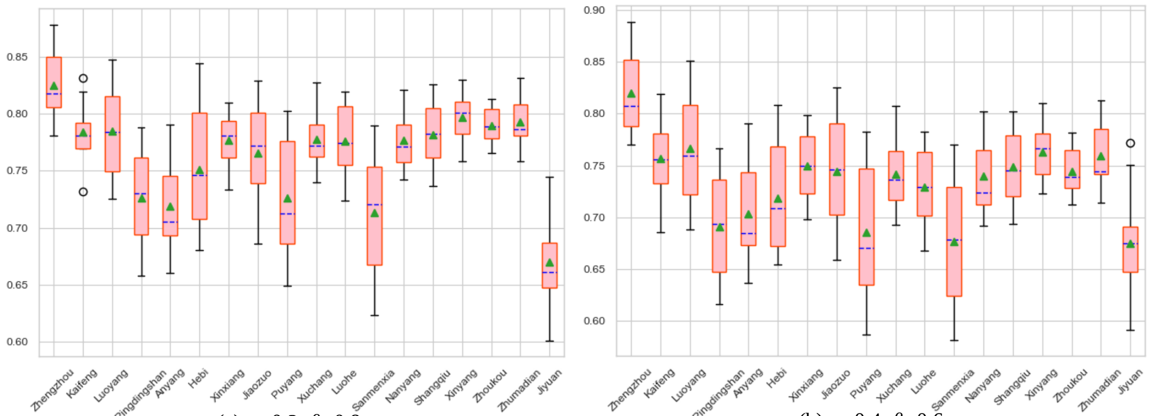
5.1. Comparison between Fuzzy BWM and Fuzzy AHP in this case study

Fuzzy AHP is another technique to determine the weight of criteria with uncertainty and ambiguity, and we will discuss the comparison between these two methods. To obtain the fuzzy weights of the criteria by fuzzy AHP, the consistency ratio calculation will follow the method suggested by Saaty (1980) and Gogus and Boucher (1998). The execution of Fuzzy AHP was presented in Appendix D. We can see that the method of Fuzzy AHP needs more comparisons than Fuzzy BWM. In addition, the consistency ratio for the criteria of these two sub-systems in Fuzzy AHP can also be calculated, which are 0.0827 and 0.0449, larger than the consistency ratio of 0.0610 and 0.0267 for Fuzzy BWM. So, we can conclude that Fuzzy BWM shows better consistency than the traditional BWM, due to the consideration of ambiguity and intangibility.

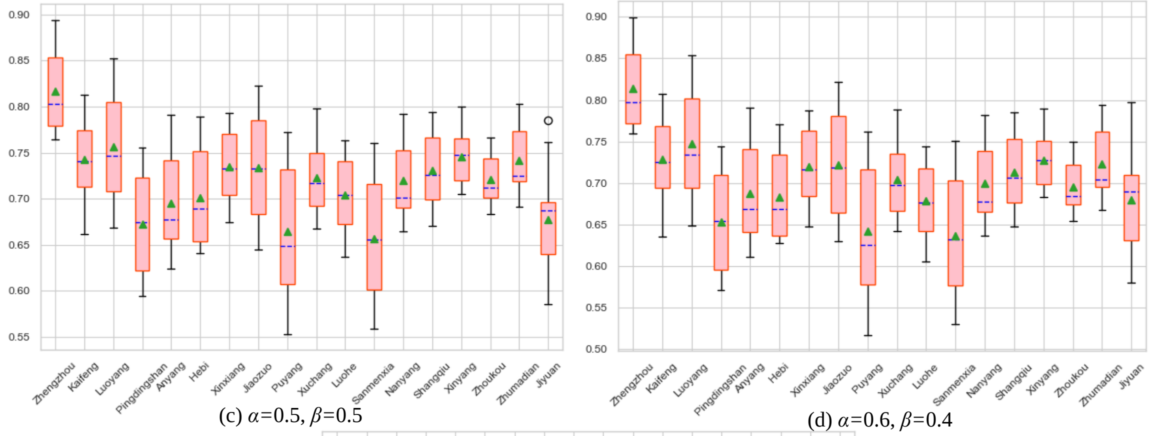
5.2. Sensitivity analysis of CCD model

According to traditional CCD model, the coupling coordination degree between economic development and air quality can be calculated by Eqs. (13)—(15). However, the determination of contribution coefficients of the subsystems in traditional CCD models depends on the requirements and inclination, which is defined subjectively and arbitrarily, and may affect its effectiveness. To test that, we defined five scenarios based on different contribution coefficients, namely: $\alpha = 0.2, \beta = 0.8$; $\alpha = 0.4, \beta = 0.6$; $\alpha = 0.5, \beta = 0.5$; $\alpha = 0.6, \beta = 0.4$; $\alpha = 0.8, \beta = 0.2$. With different coefficients, the coupling coordination degree of the 18 cities in each scenario can be derived, as shown in Appendix E. Then, we can investigate how the coupling coordination situation change with the coefficients, and the results were shown in Figure 7.

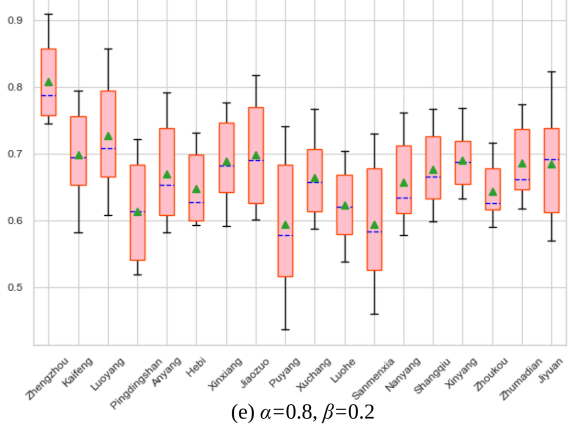
Each box diagram in Figure 7 represents a scenario, and it describes how the coupling coordination situation of the 18 cities changing with contribution coefficient within this period on average. As we can see, these cities have been ranked at different positions in different scenarios. we can also find that the maximum, minimum, mean, and median values of coupling coordination degree varies greatly in different scenarios, which greatly affects the effectiveness of this model, and may mislead policy makers.



(a) α=0.2, β=0.8 (b) α=0.4, β=0.6



(c) α=0.5, β=0.5 (d) α=0.6, β=0.4



(e) α=0.8, β=0.2

Figure 7. Traditional CCD values of 18 cities in Henan Province with different contribution coefficients (2007—2018).

Moreover, we can analyze the variance of the coupling coordination value when different contribution coefficients have been assigned to the two subsystems, and the results were displayed in Figure 8. From this radar chart, we noticed that Pingdingshan, Luohe, Puyang, and Zhoukou have the greatest variance when the two sub-systems have been allocated various weights. It indicates than the coupling coordination conditions in these cities are more sensitive to the weight of the sub-systems. Whales, Zhengzhou, Jiyuan, Anyang, Luoyang, and Jiaozuo have shown the least variance, indicating their less sensitivity to the changes of weights of sub-systems. Thus, it proved that the effectiveness of the CCD model is highly related with the contribution coefficients of the sub-systems, and the dynamic contribution coefficients is a reasonable and scientific way to determine the coefficients.

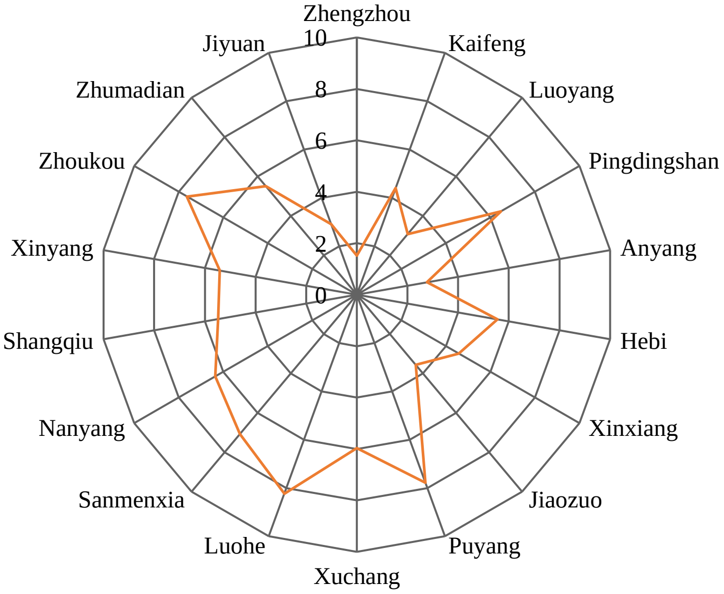


Figure 8. Average coefficient of variance of coupling coordination degree value when α=0.2, β=0.8; α=0.4, β=0.6; α=0.5, β=0.5; α=0.6, β=0.4; and α=0.8, β=0.2.

6. Policy implications

According to the performance of subsystems and coordination situation with respect to different cities and regions, we can summarize the coordination situation of the 18 cities into three types: good coordination, bad coordination with worse economic development performance, and bad coordination with worse air quality performance. Then, we can provide some policy implications for enhancing the coordination between economic development and air quality according to their economic and environmental performance.

Cities like Zhengzhou with good coordination between economic development and air quality have already achieved good performance on both sides, so the best strategy is to consolidate existing efforts and keep a balance between economic development and environment protection. Specially, as an important area in the Yellow River Basin, the strategy of ecological protection and high-quality development has provided a great opportunity to promote the economic development and air quality improvement. Moreover, as a central city of the urban agglomeration zone, Zhengzhou needs to drive the economic transformation of the surrounding cities, especially Pingdingshan and Jiyuan, to a more sustainable and cleaner economic path.

For the cities in southeast Henan Province, including Xinyang, Zhumadian, Zhoukou, and Shangqiu, more efforts should be paid on the enhancement of economic development. They used to have the best coordination performance than others, but gradually been surpassed. They have better performance in air quality than economic development, so they should promote the development of industries with local characteristics without marring the beautiful environment, such as leisure and sightseeing agriculture, characteristic livestock and poultry breeding industry, and organic food production and processing industry. So as to make good use of local environmental resources, and promote the of primary, secondary, and tertiary industries without doing damages to the environment.

Other cities, on the contrary, have shown better performance in economic development than air quality. Thus, an ecological protection development strategy is suggested for cities in the northern and western Henan Province including Puyang, Anyang, Hebi, Jiyuan, Pingdingshan, and Sanmenxia. These cities have good endowment in coal and mineral resources, which provides great advantages for local economic development. However, the resource-based industries also led to an extensive economic development model, which wastes many useful resources and generated a great deal of pollutants. Therefore, it should gradually transit to a high-quality economic development. Besides, more efforts should be paid on improving environment quality. Advanced mining and processing technologies and equipment should be introduced to reduce the wastes and pollutants emissions. More importantly, the environment protection system needs to be further explored and reformed to improve environment governance efficiency.

7. Conclusions

By proposing a framework integrating criteria selection, weight determination, performance comparison, and coordination calculation, this study can help analyze the coordination between economic development and air quality for sustainable development. Firstly, the criteria for measuring economic development and air quality are carefully and systematically selected based on literature review, theoretical analysis and workshop discussions. Then, the Fuzzy BWM are employed to determine the criteria weights based on focus group discussion. Finally, an improved CCD model that introduce dynamic contribution coefficients of the systems are used to analyze the coupling coordination between different systems. By comparing the results of Fuzzy BWM with that derived from Fuzzy AHP, it indicated that Fuzzy BWM can achieve better consistency for the pairwise comparisons of criteria importance. In addition, a sensitivity analysis on the contribution coefficients of CCD model was conducted, and it demonstrated that different contribution coefficients may result in great variance in coordination performance, and an appropriate technique for determining contribution coefficients is very important.

It also conducted a case study to perform this framework and investigate the coordination between economic development and air quality by taking the 18 cities in Henan Province of

China as examples. It indicated that the performance of economic development and air quality in this province has been improved during the period of 2007-2018, and a slow but incremental improvement in coordination between economic development and air quality has also been achieved over this period. However, great variance on the coordination were existed within this province. The central urban agglomeration zone and Huang-Huai economic zone have much better coordination performance than the north, west and southwest areas of this province, and these conclusions are generally consistent with existing research (Sun et al., 2018). This framework can be applied not only in China, but also in other countries or regions, to determine the coordination between social economy and environmental quality for achieving sustainable development.

There are also some problems that need further discussion. The first one is the results comparison between the improved CCD model and the other methods that were summarized previously. Because different methods vary greatly in the principles of measuring coordination between systems, so the following studies can focus the comparisons of different models for measuring that. Another problem that can be further explored is the specific influential and interactional mechanism among different economic development components, energy consumption, environmental policy and environmental quality, which can provide more detailed implications for policymaking.

Acknowledgements

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