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Assessment of City Sustainability Using MCDM with Interdependent Criteria Weight

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Abstract: The Capital Economic Circle is an important planning project in China. Sustainability is a key factor for the long-term development of the Capital Economic Circle. In this paper, we investigated the sustainability of 13 cities in the Capital Economic Circle using three dimensions: economy, society, and environment. The induced ordered weighted averaging (IOWA) operator was used for the aggregation of criteria data. The order-inducing variable in the IOWA operator was measure by the correlation degree of a criterion and all the other criteria. Criteria with larger order-inducing values were given more weight as they provided more support for the development of other criteria. The assessment results indicate that the sustainable development of most of the cities, except for Beijing and Tianjin, is poor, with performance values below 0.5. By comparing the development using three dimensions, it was found that poor performances of economic sustainability were the main reason for this. Additionally, all of the cities showed a sound momentum of sustainable growth even though the sustainable levels of most of the cities were not high. In terms of sustainable development across the three dimensions, the cities had the highest levels of environmental sustainability. The social sustainability of the cities, except for Beijing and Tianjin, was better than their economic sustainability. However, more than half of the cities (accounting for 53.8%) showed a decline in social sustainability, especially for Zhangjiakou, which had the highest degree of decline of 4.00%. Some suggestions have been provided on the basis of the main assessment results. For example, Beijing should invest more in education as well as further easing transportation pressure. There is room for further improvement of the social and environmental sustainability of Tianjin. The other cities should focus on developing economic sustainability as well as preventing the decline of social sustainability.

Keywords: multi-criteria decision making; sustainability assessment; interdependent criteria weight; correlation analysis; induced ordered weighted averaging operator

1. Introduction

The urbanization rate in China in 2017 was 58.5%, showing a great increase in the rate from that in 1953, which was 15.29% [1]. Within the urbanization process, city sustainable development is an important issue, as it is normally accompanied by various social-environmental problems: congestion, poor sanitation conditions, noise, and overcrowding, as well as fire and health risks [2,3]. The assessment of city sustainability performance has become popular for researchers in a wide range of fields [4–7]. However, a universally applicable assessment system has not been well established because the required conditions for city sustainability assessment are still ambiguous [8]. A widely accepted approach includes developing a framework involving a set of criteria selected from a combination of three dimensions—namely, the environmental (ecological), economic, and social dimensions [9]—which is known as the three-pillar model [10–12]. Many researchers have defined sustainability using other dimensions. Typically, culture [13,14] and governance [15,16] are the additional dimensions believed to affect sustainability in some manner [17].

Selected sustainability criteria need to be integrated to a final value which may be used for comprehensively measuring the sustainable performance of a city. This process can be viewed as a multi-criteria decision-making (MCDM) problem. Normalizing, weighting, and aggregating are the basic MCDM procedures [18]. Even through all the steps are important for the quality of the sustainability performance, the weighting step seems to have the greatest impact [19]. Many weighting methods have been chosen or developed for city sustainability assessment. Su et al. combined the analytical hierarchy process (AHP) with accelerating genetic algorithms (AGA) and proposed a new approach to work out the real number weights of various criteria used for measuring the degree of sustainable development of mineral resources of mining cities [20]. Reza et al. used the AHP as a multi-criteria decision-making technique to measure the impact of the proposed sub-criteria within the sustainability index proposed for a sustainability assessment of flooring systems in the city of Tehran [21]. Ameen et al. applied the AHP method to assigning weights for aggregating criteria scores used for a sustainability assessment of Iraq [22]. Asmelash et al. used the three-round Delphi method for the assessment of progress towards sustainable tourism development [23]. Ding et al. used entropy weight to evaluate the sustainable development of 287 cities at the prefecture level and above in China [24]. Lin et al. selected entropy as the basic method used to analyze the sustainability of urban ecosystems in Guangzhou, China [25]. Lu et al. used the coefficient-variation method to determine criteria weights in the process of investigating the sustainability of resource-based cities in Northeastern China [26]. Van de Kerk et al. constructed a sustainable society index with equal weights to measure sustainable development in the country region [27].

The works mentioned above primarily considered the decision makers' subjective judgments/preferences or the objective differences of the criteria values in the weighting process. However, the criteria involved in sustainability assessment are usually complicated and involve diverse interrelationships. For example, a city with an increase of GDP may facilitate the improvement of people's livelihood. Therefore, it is important to consider the interdependencies of criteria in the weighting process [28].

Many methods have been proposed to measure the interdependencies between criteria. For example, the Analytic Network Process (ANP), first proposed by Saaty [29], is a useful approach used for modelling the dependencies between criteria. In the ANP process, a super matrix, composed of the relative importance weights from each cluster of a network hierarchy, is developed to reflect the interaction between different clusters. Ziemba used the ANP method to solve a decision problem consisting of selecting the location and design of a wind farm. It was found that the ranking obtained with the use of the ANP was characterized by a higher quality [30]. Xu et al. used the ANP to analyze the sustainable building energy efficiency retrofit for hotel buildings [31]. The Choquet integral method is another widely used approach for measuring the dependencies between criteria. For example, Zhang et al. developed an optimization model to objectively determine the interaction coefficients and weights of multi-level criteria. Then, the overall satisfaction of an alternative was obtained by the Choquet integral method used for sustainability assessment of Jiangsu cities [32]. Angilella et al. took into account synergy and redundancy between criteria in the Choquet integral approach used for measuring rural sustainable development [33]. In this paper, we investigated the interdependency between criteria from the perspective of correlation analysis. It is supposed that if one criterion is correlated to many of the others, this criterion provides more support for the development of other associated criteria. In this case, more weight should be assigned to this criterion.

The aggregation approach plays an important role in the MCDM process. A great many aggregation methods have been developed in the literature [34–37]. In this paper we chose the ordered weighted averaging (OWA) operator [38] and one of its extensions, the induced OWA (IOWA) [39], as the basic method, which has been used in a wide range of sustainability assessments [39–42].

The reason for this is that the order-inducing variable [43] in the IOWA operator can be used to measure the correlation degree of a criterion and all the others. In this case, the criterion with larger order-inducing variables strongly correlates to the other criteria and should be given more weight. To achieve this, a programming model has been designed to determine the criteria weights by referring to the maximum entropy method studied in the OWA operator [44].

The National Development and Reform Commission (NDRC) launched the planning and formulation of the Capital Economic Circle in 2011. The Capital Economic Circle is one of the most important planning projects in China at present, and includes Beijing, Tianjin and 11 prefecture-level cities in Hebei province, such as Baoding, Tangshan, Langfang, Shijiazhuang, Cangzhou, Qinhuangdao, Zhangjiakou, Chengde, Handan, Xingtai, and Tengshui. In the regional planning approval plan in 2012, the development plan of the Capital Economic Circle was placed first, but the process has been slow. Therefore, in this paper we aim to investigate the sustainability of the cities in the Capital Economic Circle dynamically using MCDM methods, so as to provide more references for the cities' sustainable development. The main contributions of this research are as follows: (1) from the view of this method, we propose an objective weighting method by analyzing the interdependencies between criteria from the perspective of correlation analysis; (2) from the viewpoint of the assessment results, we find that the sustainable development of most of the cities, except for Beijing and Tianjin, is poor. In addition, some special suggestions are provided according to the assessment results.

The rest of the paper is organized as follows. Section 2 provides a brief introduction to the study cases. Section 3 proposes the assessment methods, including the construction of sustainability criteria, the interdependent criteria weighting method, and the IOWA aggregation approach. The assessment results are shown in Section 4. Conclusions, suggestions, and possible future works are outlined in Section 5.

2. Study Cases

The Capital Economic Circle is an important region in China which aims at the coordinated development of Beijing, Tianjin, and Hebei province. Beijing is the capital of China as well as its national political center, cultural center, international exchange center, and science and technology innovation center. It lies between longitudes 115°25′ E and 117°30′ N, and between latitudes 39°26′ N and 41°03′ E. Tianjin is a direct-controlled municipality and national central city. It lies between longitudes 116°43′ E and 118°04′ N, and between latitudes 38°34′ N and 40°15′ E. Hebei province has jurisdiction over 11 prefecture-level cities, and lies between longitudes 113°04′ E and 119°53′ N, and between latitudes 36°01′ N and 42°37′ E. The locations of Beijing, Tianjin, and 11 prefecture-level cities in the Capital Economic Circle are shown in Figure 1. Brief profiles of these 13 cities are shown in Table 1.

Figure 1. Locations of the studied cities in the Capital Economic Circle.

Table 1. Specifications of the 13 cities in the Capital Economic Circle, China.

City	Population	Area (km^2)	Water Resources (10,000 m^3)	Per-Capita GDP (USD) *
Beijing	13,630,000	16,411	351,000	17,505.12
Tianjin	10,440,000	11,917	189,200	17,039.35
Shijiazhuang	10,380,000	13,056	276,800	8171.71
Tangshan	7,600,000	13,472	223,600	12,031.50
Qinhuangdao	2,980,000	7802	215,300	10,923.12
Handan	10,550,000	12,065	178,500	5222.75
Xingtai	7,880,000	12,433	146,000	4004.33
Baoding	12,070,000	22,185	264,700	4441.82
Zhangjiakou	4,700,000	36,797	177,600	4908.33
Chengde	3,830,000	39,493	173,000	6033.74
Cangzhou	7,800,000	14,035	65,300	7023.64
Langfang	4,700,000	6382	70,800	8733.75
Hengshui	4,550,000	8815	65,000	4732.54

* Exchange rate: 1 USD = 6.7514 RMB as of 15 January 2019.

3. Methods

The primary purpose of this paper was to evaluate the sustainable development of cities in the Capital Economic Circle, China, in the years 2011 to 2016. The year 2011 was selected as the base period as the planning of the Capital Economic Circle was formally proposed in 2011. The year 2016 was chosen as the end period since criteria data have only been published to 2016 at present. Assessment results were used to understand the sustainability levels of the cities and provide some technology or policy references for the cities' sustainable development. To achieve this, we proposed the following framework, which is shown in Figure 2. The key methods used are discussed in the following subsections.

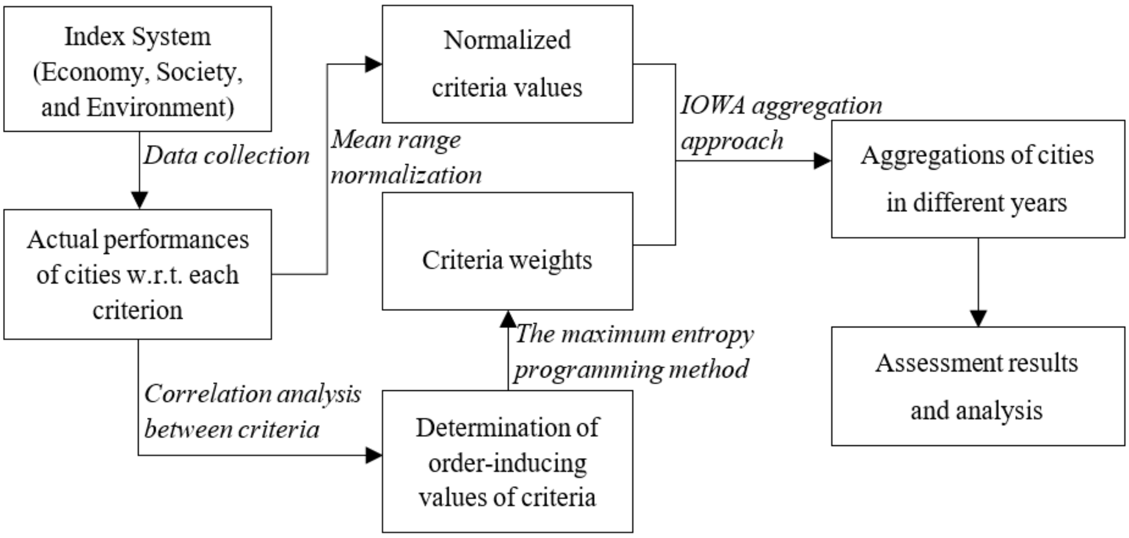


Figure 2. The framework of the study. Legend: IOWA, induced ordered average weighting.

3.1. Index System

In this paper, we defined city sustainability as pursuing all-round development, especially regarding the economic, social, and environmental dimensions. The assessment of city sustainability was developed by selecting a collection of criteria from the three dimensions. However, there are no commonly recognized criteria used for measuring city sustainable development [45]. In this paper, a set of 18 criteria was selected by referring to the main literature reviews about city sustainability in China [24,26,31,46–49]. Note that we only chose 18 criteria, which strictly speaking are not sufficient for sustainability assessment, because we were fettered by the accessibility of criteria data. All of the selected criteria were grouped into three dimensions—economy, society, and environment—as shown in Table 2.

Economic sustainability serves as a guarantee of city sustainable development. We considered the quantity of economic growth as well as the quality of economic development. As an important criteria of economic sustainability, C_1 directly reflects the economic level of an individual city; C_2 points to the situation of economic growth; C_3 indicates the development of the service industry; C_4 is used to measure the richness of residents; C_5 reflects the level of economic openness of a city; and C_6 represents the people's consumption level and their purchasing power of social commodities [24].

Social sustainability is the ultimate goal of city sustainable development. It covers the basic aspects of population, education, science and technology, health care, job opportunities, and others. For the criteria in the social sustainability dimension, C_7 reflects the distribution and density of the population of a city; C_8 and C_9 show the attention levels given to education and science and technology, respectively; C_{10} reflects the current situation of health care within a city; C_{11} indicates the state of unemployment; and C_{12} is used to reflect the degree of traffic, which ensures communication and transportation of social and economic activities [24].

Environmental sustainability is the basis for city sustainable development. We primarily focused on greening construction, environmental protection, pollution controls, and treatment. In Table 2, C_{13} and C_{14} reflect the level of green cover within a city region; C_{15} and C_{16} show, respectively, the situation of waste water discharge and air pollution in industry processes; and C_{17} and C_{18} reflect the status of pollution treatment of industrial solid waste and consumption waste, respectively.

Table 2. Criteria for sustainability assessment of cities in the Capital Economic Circle in China.

Dimension	Criteria [Code]	Unit	Property	Weight
Economy	GDP per capita [C_1]	Yuan	Benefit	0.0618
	GDP growth rate [C_2]	%	Benefit	0.0345
	Proportion of GDP generated by the service industry [C_3]	%	Benefit	0.0800
	Household saving deposits [C_4]	10,000 yuan	Benefit	0.0659
	Amount of foreign investment actually utilized per capita [C_5]	USD	Benefit	0.0509
	Retail sales of consumer goods per capita [C_6]	Yuan	Benefit	0.0703
Society	Population density [C_7]	Person/km^2	Benefit	0.0324
	Ratio of education expenditure and public finance expenditure [C_8]	%	Benefit	0.0579
	Ratio of science and technology expenditure and public finance expenditure [C_9]	%	Benefit	0.0910
	Beds of medical institutions per 10,000 people [C_{10}]	Unit	Benefit	0.0853
	Registered urban unemployment rate [C_{11}]	%	Cost	0.0368
	Per capita area of paved roads [C_{12}]	m^2	Benefit	0.0477
Environment	Ratio green coverage of built-up areas [C_{13}]	%	Benefit	0.0393
	Per capita park green area [C_{14}]	m^2	Benefit	0.0542
	Per industrial enterprise waste water discharged [C_{15}]	10,000 tons	Cost	0.0749
	Per industrial enterprise smoke and dust emissions [C_{16}]	Ton	Cost	0.0304
	Ratio of industrial solid wastes comprehensively utilized [C_{17}]	%	Benefit	0.0420
	Ratio of consumption wastes treated [C_{18}]	%	Benefit	0.0447

3.2. Weighting and Aggregation Methods

We used the IOWA operator for the integration of the criteria values. Without loss of generality, let $x_{ij}(t_k)$ denote the actual performance of the alternative (or city) O_i for criterion C_j in the year t_k, where $i \in \{1, 2, \cdots, n\}$, $j \in \{1, 2, \cdots, m\}$, $k \in \{1, 2, \cdots, N\}$. Let $y_i(t_k)$ represent the assessment value of the alternative O_i in the year t_k obtained by the IOWA operator. Assume f is mapping $R^m \to R$, which has a weighting vector $\boldsymbol{\omega} = (\omega_1, \omega_2, \cdots, \omega_m)$ with $\omega_j \in [0, 1]$ and $\sum_{j=1}^{m} \omega_j = 1$ such that

$$y_i(t_k) = f(< u_1, r_{i1}(t_k) >, < u_2, r_{i2}(t_k) >, \cdots, < u_m, r_{im}(t_k) >) = \sum_{j=1}^{m} \omega_j r_{ij}(t_k) \tag{1}$$

where ω_j is the weight associated with the criterion having the jth largest order-inducing variable u_j, and $r_{ij}(t_k)$ is the associated normalized criterion value of alternative O_i in the year t_k.

Before using Equation (1) to calculate the assessment values, we first needed to normalize the actual performance values, determine the order-inducing variable values, and obtain the associated weighting vectors. Many normalization methods have been developed [50,51] in applications. We used the mean range method for dynamic situations to improve the comparability of the assessment values for different years [52], such as

$$\begin{cases} r_{ij}(t_k) = \frac{x_{ij}(t_k) - x_{\max(j)}}{x_{\max(j)} - x_{\min(j)}}, \ if\ C_j\ is\ a\ benefit\ criterion \\ r_{ij}(t_k) = \frac{x_{\max(j)} - x_{ij}(t_k)}{x_{\max(j)} - x_{\min(j)}}, \ if\ C_j\ is\ a\ cost\ criterion \end{cases} \tag{2}$$

where $x_{\max(j)}$ and $x_{\min(j)}$ are the maximum and minimum values of criterion C_j across the years t_1 to t_N.

We used the order-inducing variable u_j to measure the correlation degree of criterion C_j and all the other criteria. The Pearson correlation coefficient was selected to calculate the correlation coefficient of any two criteria, denoted as ρ_{ij}, where $\rho_{ij} \in [-1, 1]$, $i, j = 1, 2, \cdots, m$. Generally, if $|\rho_{ij}| \geq 0.1$, that criterion C_i correlates with criterion C_j. When $|\rho_{ij}| \geq 0.5$, criterion C_i has a strong correlation with criterion C_j. For criterion C_j, we counted the times it correlated with other criteria and denoted this τ_j. If the value of τ_j is close to m, C_j correlates with most of the other criteria. In this case, the criterion should be given more weight. Therefore, we let $u_j = \tau_j$ and rearranged the criteria in descending order according to u_j. In the case of a tie, we calculated the average of the absolute value of the correlation coefficients equal to or greater than 0.1, denoted as $\overline{\rho}_j$, and then rearranged the associated criteria using $\overline{\rho}_j$. This process was formulated using

$$\begin{cases} \tau_j = count(|\rho_{ij}| \geq 0.1) \\ \overline{\rho}_j = \frac{1}{\tau_j} \sum_{k=1}^{\tau_j} |\rho_{kj}| \text{ with } |\rho_{kj}| \geq 0.1 \end{cases} \quad (3)$$

where $count(|\rho_{ij}| \geq 0.1)$ represents the total number of times criterion C_j satisfies the condition $|\rho_{ij}| \geq 0.1$.

The calculated values of the order-inducing variable u_j are shown in Table 3 in Section 4.1.

Table 3. The ranks of criteria and their order-inducing values.

Rank	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Criterion	C_9	C_{10}	C_3	C_{15}	C_6	C_4	C_1	C_8	C_{14}
$u_j = \tau_j$	16	15	15	15	14	14	14	14	13
$u_j = \overline{\rho}_j$	-	0.5648	0.5352	0.2861	0.6116	0.5765	0.5362	0.3603	0.6030
Rank	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Criterion	C_5	C_{12}	C_{18}	C_{17}	C_{13}	C_{11}	C_2	C_7	C_{16}
$u_j = \tau_j$	13	13	12	11	10	10	9	7	3
$u_j = \overline{\rho}_j$	0.4533	0.3822	-	-	0.3177	0.1455	-	-	-

Note: "-" indicates that the value of $\overline{\rho}_j$ did not need to be calculated as the associated τ_j value is unique.

For the ordered criteria, more weight should be given to the element located on the top. That is, the weighting vector should satisfy the condition $\omega_i \geq \omega_j$ when $i \leq j$ in Equation (1). Motivated by the maximum entropy method first provided by O'Hagan [44] in 1988, we used the following constrained nonlinear optimization model to calculate the associated weights.

$$\max \quad Disp(\boldsymbol{\omega}) = -\sum_{j=1}^{m} \omega_j \ln \omega_j \quad (4)$$

$$s.t. \quad orness(\boldsymbol{\omega}) = \alpha = \frac{1}{m-1} \sum_{j=1}^{m} (m-j)\omega_j, \quad \alpha > 0.5 \quad (5)$$

$$\omega_i \geq \omega_j \quad for \quad i \leq j, \quad i, j = 1, 2, \cdots, m \quad (6)$$

$$\sum_{j=1}^{m} \omega_j = 1, \quad \omega_j \in [0, 1] \quad (7)$$

The *orness* value α was designed to measure the attitude of the decision maker. When $\alpha > 0.5$ more weight is assigned to the top of the weighting vector. To avoid the situation of unreasonable variance between criteria weights, we let $\alpha = 0.6$ and calculated the associated weights using the optimization model (4)–(7) as shown in the last column of Table 2.

4. Results and Discussion

The actual criteria data were extracted from the Beijing Statistical Yearbook (2012–2017) [53], the Tianjin Statistical Yearbook (2012–2017) [54], the Hebei Provincial Statistical Yearbook (2012–2017) [55], and the China City Statistical Yearbook (2012–2017) [56]. The collected criteria values of individual cities are shown in the Appendix A section.

4.1. Asssessment Results

For the collected criteria values, we calculated the order-inducing values of the criteria according to Equation (3). The ranking of criteria and the associated order-inducing values are shown in Table 3.

We normalized the criteria values, shown in Appendix A, by Equation (2). Then, we aggregated the normalized criteria values and the associated weights shown in the last column of Table 2 through Equation (1). We obtained the sustainable performances of the 13 cities for the years 2011 to 2016, as shown in Table 4.

Table 4. Sustainable performances of the 13 cities in the Capital Economic Circle, China.

City	2011		2012		2013		2014		2015		2016	
	V [a]	R [b]	V	R	V	R	V	R	V	R	V	R
Beijing	0.6140	1	0.6418	1	0.7088	1	0.7098	1	0.6997	1	0.7097	1
Tianjin	0.4804	2	0.5095	2	0.5485	2	0.5475	2	0.5444	2	0.5593	2
Shijiazhuang	0.3672	3	0.3411	4	0.3639	3	0.3604	5	0.3755	3	0.4106	3
Tangshan	0.2979	6	0.3040	6	0.3355	5	0.3415	7	0.3513	5	0.3353	9
Qinhuangdao	0.2884	8	0.2933	8	0.2975	8	0.3898	3	0.2693	12	0.3801	4
Handan	0.3256	4	0.3566	3	0.3577	4	0.3642	4	0.3508	6	0.3513	7
Xingtai	0.2875	9	0.2500	12	0.2625	12	0.2792	11	0.3009	9	0.3234	10
Baoding	0.2690	10	0.2627	10	0.2718	11	0.2989	9	0.3131	8	0.3357	8
Zhangjiakou	0.2300	13	0.2218	13	0.2505	13	0.2459	13	0.2486	13	0.2716	13
Chengde	0.2688	11	0.2901	9	0.2845	9	0.2770	12	0.2941	11	0.3185	11
Cangzhou	0.3004	5	0.3031	7	0.3202	6	0.3422	6	0.3578	4	0.3637	5
Langfang	0.2903	7	0.3100	5	0.3041	7	0.3177	8	0.3277	7	0.3581	6
Hengshui	0.2507	12	0.2616	11	0.2807	10	0.2910	10	0.2978	10	0.3145	12

Note: [a] V represents the sustainable performance value of a city; [b] R represents the rank of a city.

4.2. Discussion

To more clearly indicate the change of performance values of the cities' sustainability across different years, graphic representations, showing the development trend of the cities' sustainability from 2011 to 2016, are shown in Figure 3.

Figure 3. Change in development trends of cities' sustainability for different years. Note: [a] This value represents the average growth rates of the sustainable performance of a city from 2011 to 2016, calculated by $(y_i(2016) - y_i(2011))/y_i(2011)/5 \times 100\%$; [b] This value represents the maximum sustainability performance of a city.

Using Table 4 and Figure 3, these conclusions may be drawn:

(1) The sustainable development levels of Beijing and Tianjin were apparently higher than those of the other cities. The maximum performance values of the cities, except for Beijing (0.7098) and Tianjin (0.5593), were below 0.5. This indicates that the cities located in Hebei province had poor sustainability.

(2) Although the sustainable levels of most of the cities were not high, all of the cities showed positive growth rates. This indicates the cities maintained a sound momentum of sustainable growth. The sustainable growth rates of Qinhuangdao and Hengshui were significant, being over 5%. However, the performance of Qinhuangdao was highly volatile in the sustainability process for the years 2013 to 2016.

(3) The sustainability of the four cities Shijiazhuang, Tangshan, Handan, and Xingtai showed slow development as the average growth rates of these cities' sustainable performances were below 3%. Notably, the growth rate of Handan was 1.58%.

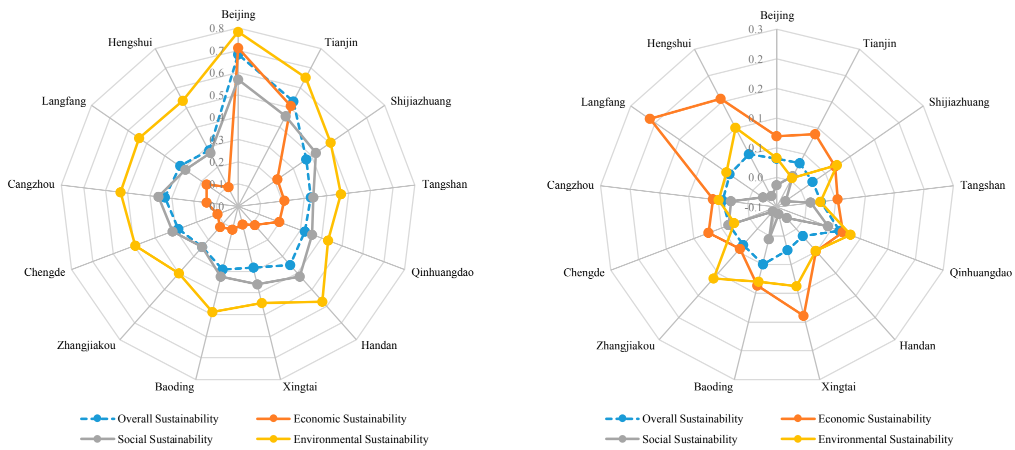
More detailed discussion of the sustainable development of the cities using the three dimensions was given to explore the profound reasons for why the cities' sustainability was poor, especially for the cities in Hebei province. The weights of the criteria belonging to each dimension—economy, society, and environment—were calculated by normalizing the associated criteria weights as shown in the last column of Table 2. Then, the IOWA operator was used to integrate the criteria values and associated weights to obtain the performance values of each dimension. The average performances of the cities' sustainability for the years 2011 to 2016 and the average growth rates are shown in Table 5.

Table 5. The average sustainability development of cities with regard to different dimensions.

City	Overall Sustainability [a]		Economic Sustainability			Social Sustainability			Environmental Sustainability		
	V	R	V	R	G [b]	V	R	G	V	R	G
Beijing	0.6806	1	0.7091	1	6.98%	0.5695	1	−1.35%	0.7811	1	3.24%
Tianjin	0.5316	2	0.5087	2	8.83%	0.4576	2	0.81%	0.6518	2	0.54%
Shijiazhuang	0.3698	3	0.2124	3	6.93%	0.4229	3	−3.23%	0.5047	7	7.39%
Tangshan	0.3276	6	0.2096	4	5.38%	0.3388	8	0.73%	0.4639	10	2.44%
Qinhuangdao	0.3198	7	0.1982	5	6.86%	0.3552	7	4.27%	0.4309	12	8.29%
Handan	0.3510	4	0.1123	9	4.98%	0.4192	4	−2.53%	0.5710	3	4.87%
Xingtai	0.2839	11	0.0821	13	13.92%	0.3606	5	−3.77%	0.4463	11	8.77%
Baoding	0.2919	9	0.1064	10	8.66%	0.3236	9	0.56%	0.4889	9	8.04%
Zhangjiakou	0.2447	13	0.1232	8	4.44%	0.2431	13	−4.00%	0.4014	13	11.09%
Chengde	0.2888	10	0.1002	11	7.33%	0.3164	10	3.77%	0.4949	8	2.72%
Cangzhou	0.3312	5	0.1439	7	5.93%	0.3605	6	2.82%	0.5337	6	4.91%
Langfang	0.3180	8	0.1708	6	21.09%	0.2900	11	−2.21%	0.5396	4	5.38%
Hengshui	0.2827	12	0.0972	12	15.57%	0.2701	12	−2.97%	0.5342	5	10.02%

Note: [a] Overall sustainability represents the sustainability across the three dimensions; [b] G represents the average growth rate of sustainable performance of a city from the year 2011 to 2016; the average growth rates of overall sustainability of the cities are shown in Figure 3.

To more clearly compare the differences between the average development levels and growth rates among the cities, we created graphics which compare the cities on the basis of the three dimensions, as shown in Figure 4.



(a) (b)

Figure 4. Comparison of cities' average development levels and growth across different dimensions. (**a**) Comparison of the average performances. (**b**) Comparison of the average growth rates.

Using Figure 4 and Table 5, these conclusions may be drawn:

(1) For the cities located in Hebei province, their poor sustainability was mainly caused by their unfavorable performances in economic sustainability (see Figure 4a). The maximum average performance of the cities was 0.2124 (Shijiazhuang), revealing the great difference between that value and those of Beijing (0.7091) and Tianjin (0.5087).

(2) Beijing had the best development level as it performed best across the three dimensions of economy, society, and environment. Comparatively, it had the worst performance for social sustainability (0.5695). Combined with Figure 4b, the social sustainability of Beijing showed a negative growth rate (−1.35%).

(3) All of the cities performed best in environmental sustainability, which had the largest average performance values and positive growth rates. The performances of Beijing and Tianjin for economic sustainability were better than those for social sustainability. The cities in Hebei province had

better social sustainability than economic sustainability. Although the cities, except for Beijing and Tianjin, had the worst economic sustainability, they showed optimistic growth rates (see Figure 4b). In particular, the average growth rates of Langfang, Hengshui, and Xingtai were over 10%, being 21.09%, 15.57%, and 13.92%, respectively.

(4) Overall, the development of the cities' social sustainability was not optimistic. Except for Chengde, all the other cities' growth rates for social sustainability were lower than those for the overall sustainability. In addition, more than half of the cities (accounting for 53.8%) had negative growth rates even though the development levels of their social sustainability were comparatively higher.

5. Conclusions and Suggestions

Sustainability is a very important factor in the process of the long-term development of the Capital Economic Circle. In this paper, we investigated the sustainable development of the cities in the Capital Economic Circle. The main innovation of this research is that criteria weights were determined by considering the criteria interdependences from the perspective of correlation analysis. Criteria which correlated to many of the other criteria were given more weight as they were viewed as providing more support for the development of the other associated criteria. The IOWA operator was used to aggregate the criteria data collected for the dimensions of economy, society, and environment.

The assessment results indicate that great differences exist in cities' sustainability. The sustainable development levels of Beijing and Tianjin were shown to be much higher than those of the other cities located in Hebei province. However, all the cities were revealed to have maintained a sound momentum of sustainable growth as the average growth rates for the period 2011 to 2016 were positive. Significantly, the sustainable growth rates of Qinhuangdao and Hengshui were over 5%. In terms of the sustainable development across the three dimensions, all the cities performed best in environmental sustainability. Except for Beijing and Tianjin, the social sustainability of the cities was better than their economic sustainability. However, more than half of the cities (accounting for 53.8%) had negative growth rates for social sustainability. Overall, the cities in the Capital Economic Circle need to improve their levels of economic sustainability, prevent the decline of social sustainability, and maintain current levels of environmental sustainability in future developments.

More specifically, we suggest that local authorities in Beijing should pay more attention to social sustainability development. By analyzing the actual criteria data for social sustainability, it was found that education investment and traffic conditions were two key factors. Therefore, Beijing should invest more in education. Additionally, Beijing needs to further ease the pressures of transportation. Tianjin showed slow development in both social and environmental sustainability. There is a room for further improvement in these dimensions. With respect to the cities located in Hebei province, a focus on developing economic sustainability as well as preventing the decline of social sustainability is needed. In particular, by analyzing the actual criteria data, we suggest that more investment in science and technology is needed.

In future work, the sustainability of the cities in the Capital Economic Circle will be considered from the perspective of synergetic development. Accordingly, the criteria weight will be discussed in detail from the point of coupling. Developing a forecast approach to predict the future sustainable development of cities may also be an important topic of interest. A forecast can be developed using a fuzzy approach with reference to the research of Ziemba et al. [57].

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Appendix A. Actual Criteria Values of the Cities for the Years 2011 to 2016.

Table A1. Criteria values for 2011.

Criteria	City												
	B[1]	**T[2]**	**S[3]**	**T[4]**	**Q[5]**	**H[6]**	**X[7]**	**B[8]**	**Z[9]**	**C[10]**	**C[11]**	**L[12]**	**H[13]**
C_1	81,658	85,213	39,919	71,565	35,691	30,270	20,027	21,796	25,649	31,705	36,053	36,773	21,334
C_2	8.1	16.4	12.01	11.7	12	12.15	11.6	12	11.5	12.1	12.3	8	12.13
C_3	76.07	46.16	40.07	30.98	47.72	32.66	29.16	31.36	39.69	30.18	36	34.85	28.65
C_4	189,162,355	62,060,300	32,435,792	28,412,423	9,921,179	15,691,093	12,594,158	22,890,835	9,654,155	7,646,208	15,496,754	13,546,040	9,874,306
C_5	552.04	1310.3	36.83	146.69	207.71	66.88	2.18	38.40	39.97	15.22	39.85	135.38	33.34
C_6	53,997.38	34,073.26	16,674.89	18,108.79	13,611.00	8624.51	7355.84	8774.74	8173.87	8118.63	9306.35	11,605.44	8484.12
C_7	990.51	1103.26	8063.4	2497.65	1699.81	3429.26	5317.04	3463.46	2391.76	759.14	2963.39	2772.6	1819.41
C_8	0.1603	0.1683	0.2169	0.1773	0.1515	0.2134	0.2341	0.1980	0.1754	0.2017	0.2057	0.1905	0.2170
C_9	0.0564	0.0335	0.0157	0.0140	0.0064	0.0081	0.0050	0.0047	0.0044	0.0071	0.0043	0.0122	0.0049
C_{10}	68.55	44.82	37.88	43.56	40.42	31.80	30.73	27.30	31.98	35.95	32.18	35.24	27.90
C_{11}	0.0301	0.0868	0.1174	0.1591	0.1367	0.0812	0.0557	0.1213	0.1047	0.1254	0.0621	0.0321	0.0687
C_{12}	7.59	12.85	17.07	9.79	21.11	21.39	19.99	17.86	14.41	11.93	17.32	10.76	13.65
C_{13}	51.59	34.51	47.22	40.06	49.4	49.32	39.1	44.89	40.72	39.06	36.27	46.18	41.11
C_{14}	14.24	6.85	3.61	3.96	6.45	3.28	1.37	1.34	2.03	3.40	0.80	1.61	1.01
C_{15}	2.31	3.95	10.76	13.44	16.83	8.23	17.14	11.00	13.45	4.06	7.06	7.38	5.59
C_{16}	7.86	13.03	40.40	393.24	184.06	252.89	107.17	25.29	112.16	112.56	36.53	28.01	21.66
C_{17}	66.26	99.79	49.47	73.32	37.04	50.02	92.25	48.16	23.27	4.74	49.95	49.61	49.94
C_{18}	98.24	100	100	91.33	100	100	100	100	82	100	90.25	96.87	18.11

Note: B[1] represents Beijing; T[2] represents Tianjin; S[3] represents Shijiangzhuang; T[4] represents Tangshan; Q[5] represents Qinhuangdao; H[6] represents Handan; X[7] represents Xingtai; B[8] represents Baoding; Z[9] represents Zhangjiakou; C[10] represents Chengde; C[11] represents Cangzhou; L[12] represents Langfang; H[13] represents Hengshui.

Table A2. Criteria values for 2012.

Criteria	City												
	B[1]	**T[2]**	**S[3]**	**T[4]**	**Q[5]**	**H[6]**	**X[7]**	**B[8]**	**Z[9]**	**C[10]**	**C[11]**	**L[12]**	**H[13]**
C_1	87,475	93,173	43,552	76,643	37,804	32,650	21,361	24,053	28,139	33,791	38,949	40,598	23,101
C_2	7.73	13.8	10.38	10.4	9.1	10.5	9.5	10.5	10	10.5	10.6	9.7	10.4
C_3	76.46	46.99	40.16	31.72	47.33	33.71	30.16	31.12	40.43	31.42	36.06	34.96	29.58
C_4	214,045,510	70,553,800	37,354,986	33,050,711	11,501,932	17,908,067	14,547,114	26,570,092	11,197,512	8,882,165	18,456,510	15,815,550	11,603,919
C_5	619.78	1511.9	84.36	165.85	215.64	80.58	13.34	46.97	53.29	34.61	47.84	143.16	41.46
C_6	59,366.60	39,482.77	19,056.61	20,693.13	15,584.06	9804.43	8346.29	10,018.90	9385.06	9278.90	10,585.32	13,113.62	9765.67
C_7	790.6	844.56	634.36	550.6	373.26	823.09	601.42	528.33	127.03	95.31	529.68	673.85	500.67
C_8	0.1706	0.1767	0.2355	0.1990	0.1744	0.2512	0.2293	0.2059	0.1937	0.2182	0.2368	0.2098	0.2285
C_9	0.0543	0.0357	0.0162	0.0216	0.0060	0.0128	0.0047	0.0050	0.0049	0.0067	0.0047	0.0126	0.0046
C_{10}	71.38	49.23	41.38	38.01	36.29	33.64	31.70	31.60	25.63	42.60	26.70	35.49	29.95
C_{11}	0.0151	0.0822	0.1169	0.1348	0.1604	0.0816	0.0556	0.1254	0.0898	0.1239	0.0628	0.0301	0.0763
C_{12}	7.53	14.29	17.34	9.35	21.46	22	17.94	18.28	14.7	12.11	17.54	10.82	13.43
C_{13}	51.92	34.89	41.06	40.62	48.98	49.3	39.31	36.94	41.45	39.75	37.1	46.3	38.93
C_{14}	15.09	6.89	3.54	3.99	6.62	3.30	1.36	0.95	2.07	3.57	0.82	1.60	0.98
C_{15}	2.49	3.58	13.01	14.79	14.91	6.08	15.02	9.78	14.40	3.08	6.58	5.23	4.98
C_{16}	8.35	11.05	41.19	312.68	194.18	201.43	90.56	22.75	70.21	61.01	26.98	24.57	14.81
C_{17}	78.96	99.62	49.47	73.32	37.04	50.02	48.25	48.16	23.27	4.74	49.95	49.61	49.94
C_{18}	99.12	99.8	100	91.33	100	100	100	84.455	85	100	92.61	95.7	41.815

Table A3. Criteria values for 2013.

Criteria	City												
	B[1]	**T[2]**	**S[3]**	**T[4]**	**Q[5]**	**H[6]**	**X[7]**	**B[8]**	**Z[9]**	**C[10]**	**C[11]**	**L[12]**	**H[13]**
C_1	148,181	143,129	48,491	82,831	39,889	30,800	21,030	24,951	28,201	33,653	39,960	46,046	23,889
C_2	9.07	11.45	8.08	4.43	2.58	1.23	4.73	6.74	6.76	7.63	7.13	8.29	5.86
C_3	76.85	48.05	41.44	32.27	47.03	35.76	31.74	31.54	39.56	32.38	37.34	37.16	32.1
C_4	229,043,566	76,123,070	41,575,970	36,527,884	13,116,573	20,141,656	16,559,275	30,362,317	12,686,186	10,324,862	20,924,394	18,294,251	13,085,517
C_5	647.59	1676.2	97.74	182.99	252.22	88.91	60.26	53.26	59.30	10.94	54.39	162.24	45.22
C_6	63,626.22	44,526.18	19,660.61	23,346.54	17,580.05	11,128.60	9286.41	10,486.18	10,704.10	10,382.82	11,749.25	15,250.55	10,977.42
C_7	802.11	842.47	632.98	537.57	375.19	823.89	613.58	556.89	126.61	95.17	536.77	661.83	507.08
C_8	0.1632	0.1810	0.2221	0.1956	0.1669	0.2328	0.2108	0.1698	0.1683	0.2018	0.2000	0.1834	0.1837
C_9	0.0562	0.0364	0.0153	0.0182	0.0069	0.0147	0.0050	0.0053	0.0046	0.0082	0.0059	0.0108	0.0043
C_{10}	87.58	52.85	47.67	51.82	47.58	35.79	35.14	29.99	41.29	41.59	35.31	36.81	33.85
C_{11}	0.0106	0.1221	0.1096	0.1480	0.2450	0.0426	0.0420	0.1134	0.0897	0.1075	0.0634	0.0325	0.0652
C_{12}	7.72	15.14	18.07	10.07	21.59	22.65	15.74	22.79	15.79	14.83	17.63	10.74	16.76
C_{13}	51.11	35.46	42.89	41.14	56.16	46.42	37.42	41.41	41.45	41.02	36.88	44.15	41.54
C_{14}	15.51	7.25	3.77	4.02	6.76	3.00	1.40	1.09	2.31	3.49	0.77	1.64	1.00
C_{15}	2.61	3.47	12.19	9.35	15.16	6.09	12.82	8.96	10.97	3.04	4.48	4.30	5.17
C_{16}	7.47	11.66	46.12	355.29	192.34	182.96	87.84	24.53	77.38	59.43	27.41	20.47	14.67
C_{17}	86.58	99.39	98.61	73.32	49.32	95.4	94.47	89.64	38.93	5.49	99.58	98.9	99.77
C_{18}	99.3	96.8	73.54	88.34	90.22	100	99.86	68.91	87.58	85.86	74.44	27.16	65.52

Table A4. Criteria values for 2014.

Criteria	City												
	B[1]	**T[2]**	**S[3]**	**T[4]**	**Q[5]**	**H[6]**	**X[7]**	**B[8]**	**Z[9]**	**C[10]**	**C[11]**	**L[12]**	**H[13]**
C_{1}	99,995	10,5231	48,970	80,450	39,282	32,943	22,758	26,501	30,540	38,128	42,676	48,407	26,022
C_{2}	7.3	10	7.9	5.1	5	6.5	6	7.1	5.24	7.84	8	8.2	8.2
C_{3}	77.95	49.34	43.81	33.27	48.01	36.8	36.04	34.48	39.58	33.2	37.89	42.5	37.65
C_{4}	239,722,163	79,168,974	43,876,724	39,905,102	14,476,204	22,516,785	18,590,332	33,889,235	14,175,021	11,398,186	23,316,767	20,718,058	14,641,503
C_{5}	678.03	1855.7	99.71	186.79	275.20	89.89	62.88	50.63	69.39	39.24	44.56	159.23	47.79
C_{6}	72,281.36	46,608.19	23,645.88	25,983.97	19,571.97	12,067.67	10,301.23	12,550.56	11,997.51	11,607.33	13,116.83	16,067.86	12,218.15
C_{7}	812.5	853.12	781.85	559.06	378.17	853.28	621.64	539.37	127.07	96.41	547.47	705.75	513.4
C_{8}	0.1640	0.1792	0.2120	0.2077	0.1691	0.2237	0.1916	0.1902	0.1561	0.1829	0.1975	0.1779	0.1510
C_{9}	0.0625	0.0378	0.0129	0.0155	0.0089	0.0167	0.0065	0.0050	0.0046	0.0066	0.0092	0.0097	0.0034
C_{10}	77.13	58.51	44.66	48.97	55.97	37.36	37.96	30.93	40.56	43.53	38.56	39.87	36.94
C_{11}	0.0090	0.1772	0.0868	0.1574	0.1405	0.0441	0.0432	0.1125	0.0803	0.0903	0.0581	0.0240	0.0493
C_{12}	7.93	15.78	12.83	9.4	21.83	17.96	16.66	22.76	15.07	12.37	17.78	10.98	13.65
C_{13}	60.41	41.82	48.98	41.17	92.87	46.52	36.89	40.49	43.38	41.91	37.15	44.42	42.89
C_{14}	20.18	7.53	4.22	3.95	6.84	2.90	1.35	1.11	2.32	3.60	0.78	1.59	0.99
C_{15}	2.49	3.46	9.26	8.74	13.04	5.00	11.53	7.83	10.66	2.73	4.32	4.11	4.20
C_{16}	6.16	20.38	40.20	335.48	123.12	236.36	105.93	29.65	88.75	134.43	28.85	30.92	19.24
C_{17}	87.67	98.91	95.1	70	65	95	95.29	86.2	44.1	6	99.88	100	99.6
C_{18}	99.59	96.23	71.98	100	157.94	100	99.02	82.37	88	88.41	93.55	29.41	100

Table A5. Criteria values for 2015.

Criteria	City												
	B[1]	T[2]	S[3]	T[4]	Q[5]	H[6]	X[7]	B[8]	Z[9]	C[10]	C[11]	L[12]	H[13]
C_1	106,497	107,960	51,043	78,398	40,746	33,450	24,256	29,067	30,840	38,505	44,819	54,460	27,543
C_2	6.9	9.3	7.5	5.6	5.5	6.76	6	7	5.8	5.54	7.7	8.8	7.6
C_3	79.65	52.15	45.84	35.55	50.2	40.03	39.41	38.2	42.12	35.82	40.8	47.1	40
C_4	239,139,670	87,437,889	48,689,313	44,661,842	15,588,828	27,072,108	21,100,425	37,437,790	15,948,766	12,744,585	26,413,681	23,774,250	17,135,029
C_5	966.13	2058.1	110.82	164.75	291.31	78.14	28.15	34.60	70.92	41.74	61.08	163.93	36.99
C_6	76,851.07	51,195.67	26,175.44	28,450.26	21,438.88	12,998.93	11,216.40	12,554.65	13,179.23	12,836.24	14,323.15	17,270.22	13,466.28
C_7	819.57	861.79	788.14	560.42	379.39	870.29	627.36	541.81	127.46	96.73	551.48	722.34	512.76
C_8	0.1491	0.1570	0.1995	0.2081	0.1858	0.1951	0.2046	0.2154	0.1659	0.1950	0.2134	0.1539	0.1616
C_9	0.0502	0.0374	0.0133	0.0108	0.0040	0.0080	0.0037	0.0039	0.0030	0.0053	0.0038	0.0086	0.0032
C_{10}	77.79	60.86	45.43	49.85	51.45	39.10	37.82	37.68	42.20	45.02	41.91	39.19	36.96
C_{11}	0.0096	0.1770	0.0868	0.1117	0.1343	0.0457	0.0413	0.1101	0.7010	0.0842	0.0551	0.0229	0.1069
C_{12}	7.46	13.65	13.08	9.27	15.21	17.99	17.23	13.74	15.07	12.31	17.61	11.02	13.27
C_{13}	61.00	32.65	44.42	41.17	40.17	46.64	36.17	38.41	44.08	42.89	36.72	45.53	39.87
C_{14}	21.93	8.63	4.27	3.95	7.21	2.87	1.41	1.59	2.33	3.66	0.78	1.61	1.25
C_{15}	2.53	3.43	7.98	7.47	18.39	4.43	9.15	6.55	8.11	2.50	3.75	3.62	3.69
C_{16}	3.66	13.36	31.66	292.73	4708.5	139.12	76.96	19.04	63.29	92.73	21.38	38.41	10.11
C_{17}	83.33	98.58	98	72.5	68.55	97	95.31	93	57.16	24	100	97	99.3
C_{18}	99.8	99	95.41	100	100	100	100	99.99	95	89.02	100	58.95	100

Table A6. Criteria values for 2016.

Criteria	City												
	B^1	T^2	S^3	T^4	Q^5	H^6	X^7	B^8	Z^9	C^{10}	C^{11}	L^{12}	H^{13}
C_1	118,198	115,053	55,177	81,239	73,755	35,265	27,038	29,992	33,142	40,741	47,425	58,972	31,955
C_2	6.8	9.1	6.8	6.8	7	6.08	7.1	7.2	7	6.95	7.9	8	7.8
C_3	80.23	56.44	46.44	35.5	50.75	40.26	39.49	38.61	44.53	37.68	41.7	48.6	39.96
C_4	280,120,329	91,253,832	53,482,000	48,931,575	17,411,356	30,979,895	24,023,525	41,666,122	18,166,138	14,386,586	29,593,421	28,602,556	19,245,804
C_5	955.88	2952.7	117.63	195.13	303.48	96.83	69.06	58.28	97.88	52.23	72.44	170.65	52.20
C_6	80,741.75	53,982.83	28,663.12	31,198.76	23,483.38	14,302.20	12,308.20	15,146.55	14,535.61	14,185.55	15,741.19	18,764.07	14,844.71
C_7	819.57	861.79	788.14	560.42	379.39	870.29	627.36	541.81	127.46	96.73	551.48	722.34	512.76
C_8	0.1385	0.1358	0.2134	0.1816	0.1972	0.2006	0.2015	0.2136	0.1718	0.2000	0.2113	0.1551	0.1653
C_9	0.0446	0.0338	0.0164	0.0134	0.0119	0.0083	0.0060	0.0061	0.0054	0.0079	0.0086	0.0150	0.0056
C_{10}	80.72	59.16	47.76	50.77	51.85	42.21	39.93	39.19	47.13	49.06	43.92	41.24	40.29
C_{11}	0.0241	0.0790	0.0868	0.1081	0.1200	0.2003	0.0383	0.0910	0.7909	0.0783	0.0499	0.0215	0.1037
C_{12}	7.46	13.65	13.08	9.27	15.21	17.99	17.23	13.74	15.07	12.31	17.61	11.02	13.27
C_{13}	61.58	32.81	45.45	29.28	40.37	44.76	37.43	39.1	42.9	44.08	37.03	45.81	29.46
C_{14}	22.06	9.22	4.31	3.98	7.17	3.26	1.40	1.36	2.54	3.68	0.84	1.67	1.24
C_{15}	2.55	3.46	4.82	9.27	10.96	3.56	6.96	4.03	7.23	2.84	1.88	3.77	1.87
C_{16}	2.36	11.01	19.49	312.79	136.30	87.04	61.36	7.63	65.30	83.94	5.59	23.52	6.02
C_{17}	83.33	98.99	94.96	70.79	81.89	85.7	96.03	98.84	57.16	27.5	59.73	94.29	98.97
C_{18}	99.84	94	99.54	100	100	96.67	100	93.11	95.5	95.62	100	100	100

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