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Article

Emergy-Based City's Sustainability and Decoupling Assessment: Indicators, Features and Findings

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Abstract: Decoupling human well-being and local economic growth from resources consumption and environmental degradation has been recognized as a common vision to meet global sustainability. This paper taking Shenyang city as studied case aims to measure the decoupling process by proposing a set of new emergy-based and efficiency-oriented indicators. Decoupling process was verified in period of 1995–2010, and five new indicators including economic efficiency, the environmental pressure, the emergy-based five-year yield efficiency, the investment cost for decoupling, and the job-opportunities cost for decoupling were developed and applied. The results indicate that decoupling in Shenyang shows an erratic appearance, the trajectory of economic growth, and environmental pressure show absolute decoupling, while that of economic growth and resources utilization shows frequentative bending; emergy-based economic efficiency has been improved and the environmental pressure decreased along with the economic growth but the relative job cost per unit remains almost at the same level. However, this isolated and methodology-oriented case study provided the open-mind understandings to policy-making, thus, a wider scale comparison between different cities should be carried out for more knowledge mining.

Keywords: decoupling; ecological indicator; sustainability assessment; emergy approach

1. Introduction

Today, roughly half of the world's population lives in urban areas and the share is projected to reach 60% by 2030, which will be mostly increased in developing countries [1,2]. Considering the city's role in a national governance system [3], as well as its contribution to greenhouse gas emission [4,5], resources consumption [6,7], waste generation [5,6], and pollutants emission [8], decoupling in human well-being improvement, economic growth, and ecosystem degradation with regarding to city sustainability has been taken as common recognition to meet global sustainability [9–11]. Cities attract a growing number of humans and anthropogenic assets, while natural elements suffer a decrease almost equivalent to the increase in humans and man-made assets [3,12]. During the past years, aiming to improve the understandings on a city's sustainability and served for policy-making and monitoring in reality, sets of indicators for measuring a city's sustainability have been developed by different communities [13,14]. For instance, Voula and Pedersen in their report recognized the need for sustainability indicators as tools for quantifying sustainability performance [15], The National Statistical Institute of Italy presented a provisional list of urban environmental sustainability indicators, which are of particular interest for cities in Italy [16]. Moreno and Martínez summarized the characteristics of urban sustainability in Mexican cities and said that sustainability indicators directly affected the development of communities, from households, colonies or neighborhoods to cities or regions [17]. Lynch *et al.* explored the characteristics of existing indicator systems, reviewed 22 systems with 377 indicators and a database of 145 candidate indicators were identified [18]. In general, indices for measuring sustainability consist of ecological footprint, environmental sustainability index, genuine progress indicator, human development index and city development index [14,18], and decoupling environmental pressures from economic growth has been proposed as the inter-linked objectives for enhancing cost-effective and operational environmental policies in the context of sustainability [19–22]. Previous studies on decoupling much more focused on particular sources of environmental pressure, such as natural resource utilization, energy consumption, or pollution emissions [22–24], and mostly taken countries or provinces as studied cases, while lacking of the investigations into city level decoupling research [22]. Moreover, most of the indices used in sustainability measurement separated the economic activities from natural ecosystem service, instead of combining the ecosystem service or environmental cost to economic growth [2], thus, some key questions such as "how to measure the natural values of different nonrenewable resources consumed in human activities? And how to compare the values between waste materials and environmental protection investment?" need to be addressed. Thus, a set of unified indicators need to be developed to bridge natural ecosystem service and human policy making towards to city sustainable development.

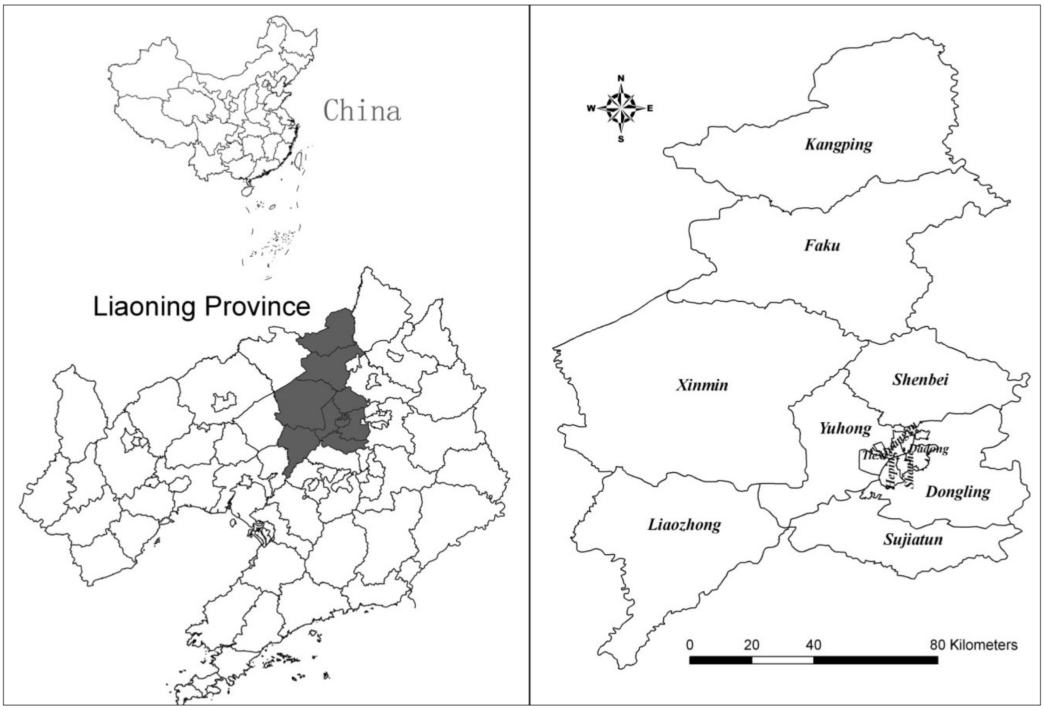
Rooted in ecology, thermodynamics, and general systems theory, Emergy is defined as the sum of all available energy inputs directly or indirectly required by a process to generate a product, which assigns value to nature's environmental effort and investment to make and support flows, materials, and services and to contribute to the economic system [6]. Emergy analysis is a technique of quantitative analysis, which determines the values of resources, services and commodities in a common unit of the solar energy it took to make them [25,26]. Thus, given the broad systemic aspects of a city's sustainability, based on emergy approach innovative indicators for measuring decoupling could be developed to achieve the target of bridging natural ecosystem service and human policy making towards to city's sustainability, therefore, a new set of indicators are developed in this study and applied in a case study—Shenyang city in Liaoning Province of China for investigating the features and findings of decoupling at city level.

2. Methodological Framework

2.1. Studied Area: Shenyang City

Shenyang is the capital city of Liaoning province and is located in the central part of Liaoning province, ranges in latitude from 41°11′ to 43°02′ N and in longitude from 122°25′ to 123°48′ E, with a total administrative area of 12,980 km^2, consisting of four counties including Kangping, Faku, Xinmin, and Liaozhong, and nine districts including Shenbei, Yuhong, Heping, Shenhe, Dadong, Huanggu, Sujiatun, Hunnan, and Dongling (Figure 1). Along with its nearby cities, Shenyang is an important industrial center in China, and serves as the transportation and commercial hub of China's northeast, particularly with Japan, Russia, and Korea.

Figure 1. Location of Shenyang City in the Liaoning Province of China.



The total population was 8.10 million in 2012, and the urban population is about 5.22 million, which make Shenyang into the largest city in Northeast China and among the top ten mega-cities in China. During the period of 1995–2010, the rural population decreased from 2.52 million to 2.50 million, while the urban population increased from 4.15 million, in 1995, to 4.69 million, in 2012. In 2012, the total GDP was 660.6 billion RMB, in which the agricultural sector (primary industry, includes agriculture, forestry, livestock, fishing, and farm sideline) accounted for 4.77%, the industrial sector (secondary industry, includes light industries and heavy industries) accounted for 51.30%, and the service industries (tertiary industry) accounted for 43.93%. The main crops grown in Shenyang are corns and rice, which in sum share about 95% of the Shenyang's total grain output. In 2003, the

Chinese central government implemented the strategy named of "revitalizing the old industrial bases in Northeastern China" and Shenyang was selected as the prior city to demonstrate this strategy, aims to shift the industrial structure to modern forms by improving resources efficiency and reducing the environmental pressure, thus, later, Shenyang was supported to built the national comprehensive reform pilot area and demonstration zone of new industrialization in China since 2010 and Shenyang also has been identified as a member of the top 20 emerging cities in China.

2.2. Indicators and Data Sources

Indicators employed in this paper has categorized as two parts: the first part is about emergy indicators which are using for understanding city's ecological economic system and providing the database for following decoupling research; the second part focus on decoupling metrics, which are identified as cost- and efficient-index, based on the raw social economic data and the calculation outcomes from emergy analysis in first part. Emergy indicators including nonrenewable resources consumption, purchased input, and waste emergy are applied in this research, based on the input and output flows' analysis [27].

2.3. Methodologies

2.3.1. Emergy Analysis

The key part of emergy analysis is to transform the natural resources and capital in human activities to a unified unit, such as the solar energy (sej, solar emjoules, a popular unit using in Emergy method) [6,25,27], while in which the key parameter is the emergy transformity (Trf.). Emergy analysis of Shenyang city is simplified as three aspects consisting of non-renewable resources (NRR) consumption in agricultural system, energy consumption (EoE) in industrial activities, and waste emissions (WE), and the value of the certain emergy transformity was extracted from different literatures, as shown in Table 1. Considering that the main idea of this paper is to investigate the decoupling between human well-being and local economic growth from resources consumption and environmental degradation, thus, in our study, only two main economic activities are considered which are agricultural sectors and industrial sectors. The main components representing the resources consumption with regard to agricultural sectors include nitrogenous fertilizer, phosphate fertilizer, potash fertilizer, compound fertilizer, pesticide, plastic membrane, and agricultural diesel oil, the other non-renewable materials are not considered due to the shortage of database; while, in industrial sectors, of course, there are many different non-renewable resources are consumed in the manufacturing processes, such as iron minerals, however, in this study, only the fossil fuels are considered, which were categorized as industrial energy consumption. The environmental pressures are measured by the total amount of waste emission from industrial and agricultural sectors, including solid waste, waste water and waste gas. Nevertheless, waste water from service sectors and households are not included and the municipal solid waste excludes from this study. All the raw social, economic and environmental data are extracted from the annual Statistical Yearbook of Shenyang city [28] and the public-accessible online database of the national statistical bureau of China [29].

Table 1. Raw indicators used for emergy analysis in Shenyang city of the year 2010.

Note	Item	Unit	Raw data	Transformity (sej/unit)	Reference	Emergy (sej/year)
Non-renewable resources of agriculture						
1	Nitrogenous Fertilizer	kg	2.86×10^{8}	6.62×10^{12}	[30]	1.89×10^{21}
2	Phosphate Fertilizer	g	7.80×10^{10}	9.35×10^{9}	[30]	7.29×10^{20}
3	Potash Fertilizer	g	5.73×10^{10}	9.32×10^{8}	[30]	5.34×10^{19}
4	Compound Fertilizer	g	2.09×10^{11}	2.80×10^{9}	[31]	5.84×10^{20}
5	Pesticide	J	9.50×10^{14}	1.97×10^{6}	[31]	1.87×10^{21}
6	Plastic Membrane	g	2.29×10^{10}	3.20×10^{9}	[32]	7.32×10^{19}
7	Agricultural Diesel Oil	g	8.23×10^{10}	2.83×10^{9}	[33]	2.33×10^{20}
Total Non-Renewable Resources (NRR)						5.44×10^{21}
Industrial Energy Consumption						
8	Coal	J	7.40×10^{17}	9.10×10^{4}	[34]	6.74×10^{22}
9	Cleaned Coal	J	7.89×10^{16}	9.10×10^{4}	[34]	7.18×10^{21}
10	Other Cleaned Coal	J	4.75×10^{15}	9.10×10^{4}	[34]	4.32×10^{20}
11	Coal Products	J	9.00×10^{14}	9.10×10^{4}	[34]	8.19×10^{19}
12	Coke	J	3.71×10^{15}	6.71×10^{4}	[35]	2.49×10^{20}
13	Natural Gas	J	2.20×10^{16}	1.71×10^{5}	[36]	3.75×10^{21}
14	Crude Oil/petroleum	J	3.04×10^{16}	1.48×10^{5}	[36]	4.5×10^{21}
15	Gasoline	g	4.04×10^{11}	2.92×10^{9}	[33]	1.18×10^{21}
16	Kerosene	J	1.50×10^{15}	5.50×10^{5}	[33]	8.27×10^{20}
17	Diesel	g	4.29×10^{11}	2.83×10^{9}	[33]	1.22×10^{21}
18	Fuel Oil	g	4.06×10^{10}	2.66×10^{9}	[33]	1.08×10^{20}
19	Liquefied Petroleum Gas	g	2.86×10^{9}	3.11×10^{9}	[33]	8.89×10^{18}
20	Electricity	J	4.10×10^{16}	1.74×10^{5}	[37]	7.14×10^{21}
Total Emergy of Energy (EoE)						9.41×10^{22}
Waste						
21	Solid waste	g	1.14×10^{13}	1.88×10^{7}	[38]	2.15×10^{20}
22	Waste water	J	3.13×10^{15}	6.66×10^{5}	[39]	2.08×10^{21}
23	Waste gas	m^3	1.30×10^{11}	6.68×10^{10}	[31]	8.69×10^{21}
Total Waste Emergy (WE)						1.10×10^{22}

2.3.2. Decoupling

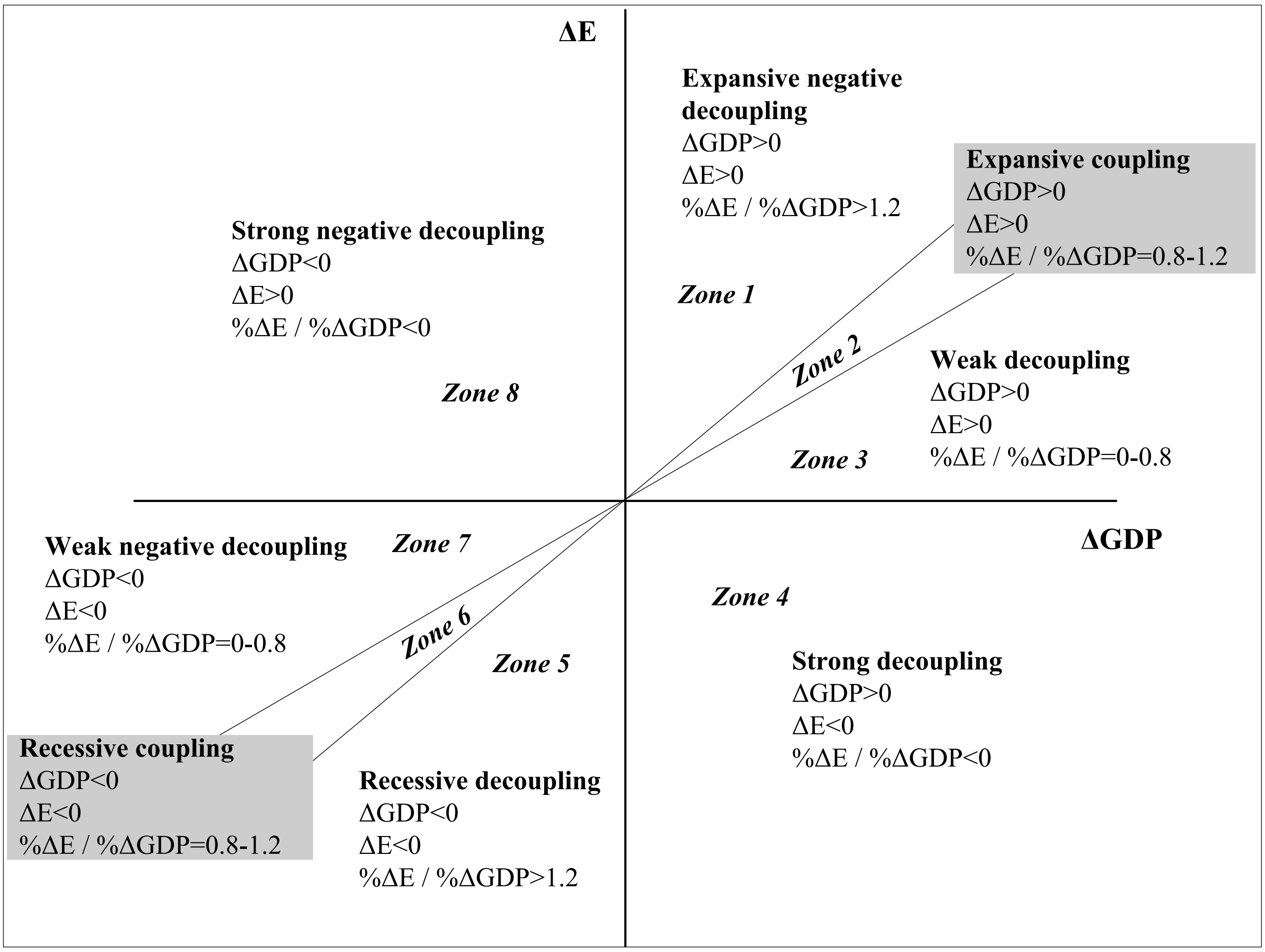
The definition of decoupling economic growth (GDP for example) from environmental problems (for example, energy consumption) was shown as in Figure 2 [40,41]. Decoupling of energy consumption growth from economic growth can be expressed as elasticity values in Equation (1):

$$\text{GDP elasticity of energy consumption} = \%\Delta E / \%\Delta GDP \qquad (1)$$

When using economic output per capita as the *X*-axis and environmental impact as the *Y*-axis, eight logical possibilities can be distinguished. In order not to over interpret slight changes as significant, a ±20% variation of the elasticity values around 1.0 (0.8–1.2) are still regarded as coupling [40,41]: (1) Expansive negative decoupling (*zone 1*), GDP and environmental impact both increase, and elasticity > 1.2; (2) Expansive coupling (*zone 2*), GDP and environmental impact both increase, and

0.8 ≤ elasticity ≤ 1.2; (3) Weak decoupling (*zone 3*), GDP and environmental impact both increase, and 0 ≤ elasticity < 0.8; (4) Strong decoupling (*zone 4*), GDP increases and environmental impact decreases, and elasticity ≤ 0; (5) Recessive decoupling (*zone 5*), GDP and environmental impact both decrease, and elasticity > 1.2; (6) Recessive coupling (*zone 6*), GDP and environmental impact both decrease, and 0.8 ≤ elasticity ≤ 1.2; (7) Weak negative decoupling (*zone 7*), GDP and environmental impact both decrease, and 0 < elasticity < 0.8; and (8) Strong negative decoupling (*zone 8*), GDP decreases and environmental impact increases, and elasticity ≤ 0. Compared to this diagram, actually, our research results mostly allocated in the right part which were illustrated as *zone 1* to *zone 4* in Figure 2.

Figure 2. Identifications and zones of decoupling [40,41].



3. Results

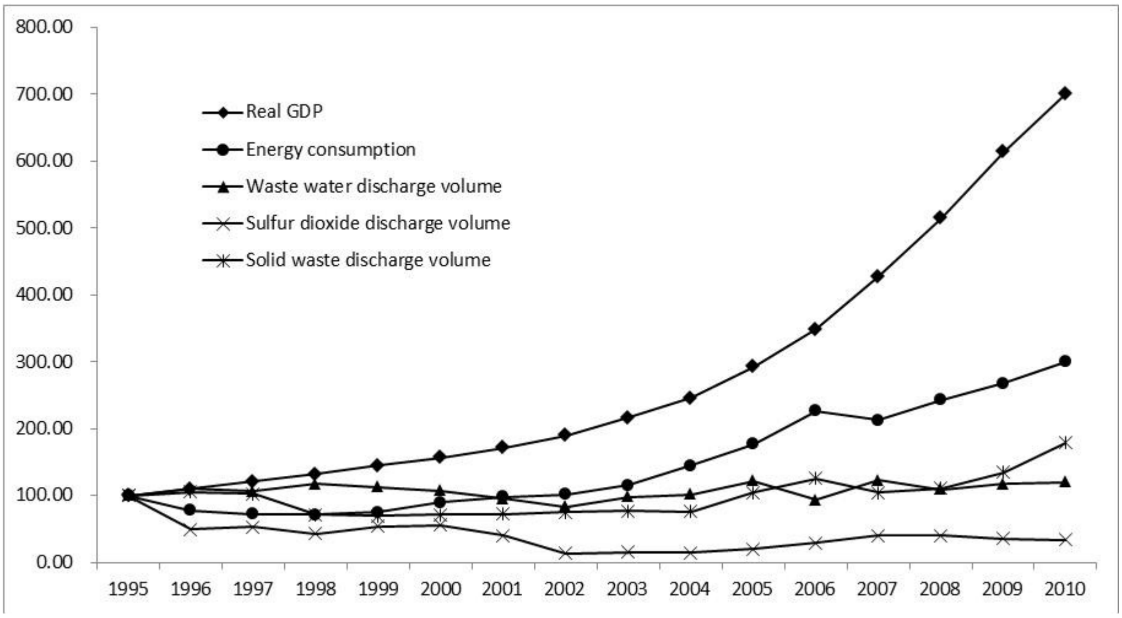
The results in this section are presented as three subsections. In the first Section, 3.1, we presented the general examine results on the decoupling process in Shenyang city from 1995–2010 by using raw indicators, based on the common method which is also usually applied in other literature; the main outcome of this sector is to provide an overall understanding on the city decoupling. In the following sections, 3.2 and 3.3, we further presented the efficiency and cost analyses of decoupling process by combining the emergy approach with economic cost and job opportunities, the main outcome of these two subsections is to offer case-based answers addressing the questions frequently concerning scientific communities and local officials as well, which have been mentioned in Section 1.

3.1. Decoupling in Shenyang City

Raw indicators used for illustrating the decoupling in Shenyang city consist of real GDP (RG), energy consumption (EC), and waste discharge (waste water, SO_2 and solid waste), which represents economic growth, resources consumption, and environmental pressure, respectively. China's rapid economic growth has triggered fast-growing pollution and energy consumption, for example, resource utilization was almost coupled with GDP due to the high consumption and dramatic increase of mineral extraction in period of 2001–2010 [22]. As in Shenyang city, the real GDP has grown six times by the year of 2010 compared to 1995, and energy consumption decreased 21.8% to 28.0% during 1996 to 2001 which mainly contributed by enterprises reorganization [42], volume of waste water discharged increased 120.7% and SO_2 discharged has decreased to 33.6%, in 2010, compared to the data of 1995, which mainly due to technology improvement and emission reduction policies [43].

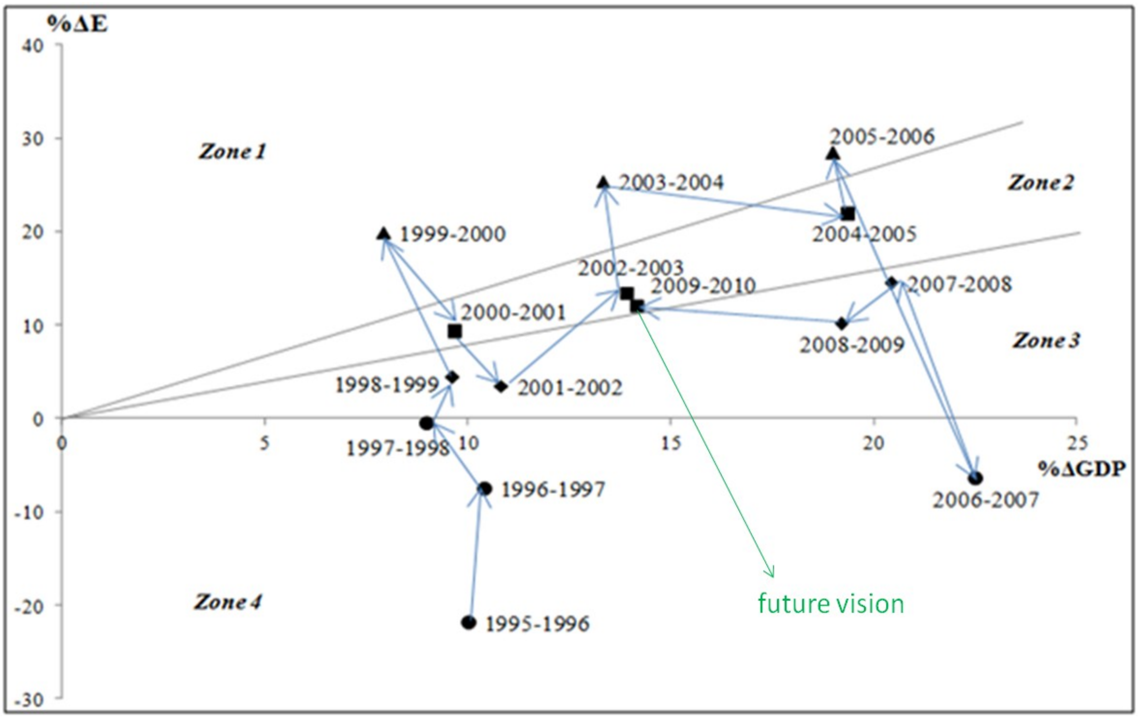
General trends of economic growth, energy consumption, and environmental pressure of Shenyang in 1995–2010 (year 1995 = 100) (Figure 3), which could be concluded that the decoupling process of Shenyang city in 1995–2010 is comprehensive complicated. The relationship between economic growth and environmental pressure shows absolute decoupling, while that of economic growth and resources utilization shows three different phases: absolute decoupling in period of 1995–2001, re-linking in period 2002–2006, and relative decoupling in period 2007–2010.

Figure 3. Trends of economic growth, energy consumption, and environmental pressure of Shenyang in 1995–2010 (year 1995 = 100).



The GDP elasticity of energy consumption in Shenyang from 1995 to 2010 shows a disordered state. The trajectory started from *zone 4* (1995–1996), crossed *zone 3* (1998–1999) and *zone 1* (1999–2000), then back to *zone 2* (2001–2002), and then repeated in *zone 1* to *zone 3*, and finally paused in *zone 2* (2009–2010) (Figure 4). Different from the decoupling at national level, which usually showed as smooth curve [2,22], decoupling degree of GDP elasticity of energy consumption at Shenyang has an erratic appearance. Given the background that Shenyang city, like most of the other cities in China, is still on the transforming phase from primary industrialization to modern industrialization (so called new-industrialization in China) [44], the situation of energy consumption sustains economic growth still exists at current and will last for a few years. With regard to the relationship between the economic growth and environmental impacts, the results show that the decoupling has happened, during 1995 to 2010, in Shenyang city, however, similar to the phenomenon shown in Figure 4, decoupling degree of economic growth and environmental impacts at city level has an erratic appearance as well. Taking the overall situation into consideration, during the period of 2000–2010, Shenyang's decoupling are mainly distributed in *zone 2* (expansive coupling) and *zone 3* (weak decoupling), which implies that various energy policies are strongly needed for shifting the current phase to strong decoupling (for instance, the future vision, shown in *zone 4*). However, given the facts that the energies are one of the main driving forces, and prerequisites as well for economic development, in order to move into *zone 4*, on one hand, the energy consumption structure in Shenyang city should be improved from fossil highlighted to renewable energies based, and diversity of renewable energies should be developed; on the other hand, methods on the improvement of energy efficiency and resources optimization as well should be implemented at current, given the existing potential in energy saving and materials reusing [3,6].

Figure 4. The GDP elasticity of energy consumption (%ΔE/%ΔGDP) in Shenyang.



3.2. Efficiency Analysis

Decoupling indicators in section 3.1 indicated that, in general the decoupling process has happened in Shenyang city during the period of 1995–2010; however, such results only could provide the qualitative knowledge for understanding the dynamic trajectory of decoupling, instead of offering quantitative guidelines and answers addressing ecological system optimization and scientific-based policy making. For example, to what degree the natural ecosystem supports regional economic growth, and how is the eco-efficiency changing along with the decoupling process? Thus, the main resources consumed for sustaining regional economic growth were calculated based on emergy theory, and then the waste discharge, which were taken as environmental impacts of human well-beings improvement to natural ecosystem, were calculated into a single criteria emergy unit.

As shown in Table 2, the total emergy input of resources (TRC)—sum of the non-renewable resources for agricultural activities (NRR) and energy consumption for industrial activities (EoE)—increased from 2.28×10^{22} sej in 1995 to 9.95×10^{22} sej in 2010, among which the emergy of the non-renewable resources (NRR) increased about two times from 1.87×10^{21} sej in 1995 to 5.44×10^{21} sej in 2010, while the emergy of energy consumption for industrial activities increased about 3.5 times from 2.09×10^{22} sej in 1995 to 9.41×10^{22} sej in 2010. In comparison, the total waste emergy (WE) decreased from 9.67×10^{22} sej in 1995 to 4.09×10^{22} sej in 2000, rebounded to 6.96×10^{22} sej in 2010, and then decreased to 1.10×10^{22} sej in 2010. Concerning on the elements aspect, the solid waste emergy contributed to a sharp drop which decreased from 8.54×10^{22} sej in 1995 to 2.15×10^{20} sej in 2010, while the waste water and waste gas almost remained at the same levels compared to those in 2010 to 1995, such changes mainly resulted from the national policies of developing circular economy which aims to improve waste recycling and resources efficiency as the *Circular Economy Promotion Law of China* was launched in 2008 [3,6] and compulsory policies on emission reduction, which aim to reduce the main pollutants in five-year plans [8], for example, the total generation of the industrial solid waste was 7.10 million tons in 2012, however, 94.3% of the total amount, about 6.72 million tons, has been recycled or reused due to the strategy of developing a circular economy in Shenyang.

Table 2. Emergy flow of agricultural and industrial activities in Shenyang city.

Items	Unit	1995	2000	2005	2010
Non-renewable resources for agricultural activities (NRR)	sej	1.87×10^{21}	2.20×10^{21}	4.45×10^{21}	5.44×10^{21}
Energy consumption for industrial activities (EoE)	sej	2.09×10^{22}	2.32×10^{22}	3.03×10^{22}	9.41×10^{22}
Total Resources Consumption (TRC)	sej	2.28×10^{22}	2.54×10^{22}	3.48×10^{22}	9.95×10^{22}
Solid waste (Esw)	sej	8.54×10^{22}	3.60×10^{22}	5.11×10^{22}	2.15×10^{20}
Waste water (Eww)	sej	2.90×10^{21}	1.86×10^{21}	2.11×10^{21}	2.08×10^{21}
Waste gas (Ewg)	sej	8.39×10^{21}	3.07×10^{21}	1.64×10^{22}	8.69×10^{21}
Total Waste Emergy (WE)	sej	9.67×10^{22}	4.09×10^{22}	6.96×10^{22}	1.10×10^{22}
Real GDP (RG)	Yuan	6.73×10^{10}	1.05×10^{11}	1.97×10^{11}	4.71×10^{11}
Economic-Efficiency (EE)	Yuan/sej	2.95×10^{-12}	4.15×10^{-12}	5.68×10^{-12}	4.73×10^{-12}
Environmental-pressure(EP)	sej/Yuan	1.44×10^{12}	3.88×10^{11}	3.52×10^{11}	2.33×10^{10}

Total emergy input of resources (TRC) herein means the natural resources exploitation for sustaining the economic development, and the total waste emergy (WE) means the pressure to environmental system resulted from the human economic activities, and Real GDP (RG) was used here as an indicator for measuring economic development. Thus, two new indicators including economic-efficiency (EE) and environmental-pressure (EP) were developed for quantifying a city's emergy-based decoupling degree. In formula, EE equals RG divided by TRC, which means how much economic value could be created based on one unit emergy natural resources, and EP equals WE divided by RG, which indicates the environmental pressure to natural ecosystem resulting from one unit economic growth. In 2010, the emergy-based economic-efficiency (EE) of Shenyang city was 4.73×10^{-12} Yuan/sej, improved from 2.95×10^{-12} Yuan/sej in 1995; while the environmental pressure (EP) decreased from 1.44×10^{12} sej/Yuan in 1995 to 2.33×10^{10} sej/Yuan in 2010, more than 60 times, which mainly resulted from the policy of developing circular economy. However, even though the amount of both waste water and gas emission almost remains the same in 1995 and 2010, shown in Table 2, in comparison, the emergy of solid waste in 1995 was 30 times to waste water and 10 times to waste gas, while in 2010 that declined to 10% and 2.45% respectively, which indicates that specific policies should be made and implemented for against the waste water discharge and air pollution at city level. The current heavy air pollution in China has demonstrated that such policies should be made as soon as possible, not only for addressing the decoupling, but also for public health.

3.3. Cost Analysis

In developing countries, the improvement of natural ecosystem usually should thank to the governmental investment in environmental protection, which was indicated as environmental protection investment (EPI) in the regional statistical system [6]. While in Shenyang city, the comparable environmental protection investment has decreased from 1.86×10^{8} Yuan in 1995 to 6.41×10^{7} Yuan in 2010. Another concern on the decoupling process is the impact on local job opportunities, which usually questioned as "does the decoupling reduce or create job opportunities?" on one hand, decoupling usually means the resources efficiency improvement, which mainly resulted from the application of advanced technologies, from this aspect, decoupling would result in job opportunities reduction; but, on the other hand, the decoupling process also encourages waste recycling for reducing the environmental pressure, which means new industries, such as environmental protection industries, would be created, and then job opportunities would be created. Thus, in order to investigate the impacts to local job opportunities, one more index, local employment, was introduced as a basic information indicator (Table 3). Here, the local employment (EPM) means the total workers number in agricultural and industrial sectors.

Table 3. Environmental protection investments and employments in Shenyang city.

Indicators	Unit	1995	2000	2005	2010
Environmental protection investment (EPI)	Yuan	1.86×10^{8}	1.06×10^{8}	6.86×10^{7}	6.41×10^{7}
Employment (EPM)	capita	2.55×10^{6}	2.07×10^{6}	1.62×10^{6}	1.48×10^{6}

Aims to measure the social cost of meeting sustainable decoupling at city level, three more new indicators were developed, which are emergy-based five-year yield efficiency (FYE), investment cost for decoupling (IfD), and job-opportunities cost (JfD). Emergy-based five-year yield efficiency (FYE) (formula: $FYE_{2000\text{–}1995} = \Delta(NRR_{2000} + EoE_{2000} - NRR_{1995}\text{-}EoE_{1995})/\Delta(RG_{2000}\text{-}RG_{1995})$) was used for measuring the decoupling degree in 1995–2000, 2000–2005, and 2010–2005, which were 6.68×10^{10} sej/Yuan, 1.02×10^{11} sej/Yuan, and 2.36×10^{11} sej/Yuan, respectively (Table 4). The reason why we applied the "five-year yield efficiency" instead of "annual yield efficiency" is due to the long-term effect of policies implementation, and could avoid the inaccuracy resulting from the annual economic oscillation. However, the investment cost for decoupling (IfD = ΔEPI/FYE), which means the investment cost for achieving one unit sej/RMB, has declined from 1.20×10^{-3} Yuan in 1995–2000 to 1.91×10^{-5} Yuan in 2005–2010; while the job-opportunities cost (JfD = ΔEPM/FYE), which was used for measuring the impulse to job-lost resulted from 1 unit sej/RMB decoupling, remains from -0.72×10^{-6} Person in 1995–2000, and -0.59×10^{-6} Person, in 2005–2010, which means that in comparison, 0.72×10^{-6} Person job opportunity would be lost in achieving one unit decoupling during 1995–2000, while 0.59×10^{-6} Person job opportunity would be lost under the same unit during 2005–2010. We could conclude that, even though the total amount of employment has decreased from 2.55×10^6 in 1995 to 1.48×10^6 in 2010 (Table 3), the impacts almost remained as the same, varying from 0.72×10^{-6} during 1995–2000 to 0.59×10^{-6} during 2005–2010 (Table 4). All in all, we could conclude that the economic cost for addressing decoupling economic growth from environmental pressure has been decreased; even though the total employments (EPM) are reduced, the relative cost per unit (JfD) remains almost at the same level.

Table 4. Cost-oriented indicators for measuring sustainable decoupling in Shenyang city.

Indicators	unit	1995–2000	2005–2010
Δ(NRR + EoE)	sej	2.54×10^{21}	6.47×10^{22}
ΔRG	Yuan	3.81×10^{11}	2.74×10^{11}
ΔFYE	sej/Yuan	6.68×10^{11}	2.36×10^{11}
ΔEPI	Yuan	-8.04×10^{7}	-4.49×10^{7}
ΔEPM	Yuan	-4.80×10^{5}	-1.40×10^{5}
IfD	Yuan	1.20×10^{-3}	1.91×10^{-5}
JfD	Person	-0.72×10^{-6}	-0.59×10^{-6}

4. Conclusions

Current research on a city's sustainability and decoupling of the economic growth from resource consumption and environmental degradation usually focus on either natural ecosystem aspect or human economic activities, but lack of the integrated research by bridging the human economic activities and the natural system capacity, and considering the social cost, such as government investment and impacts to regional job opportunities, which actually are of the utmost importance for policy makers and decision making. This paper introduced the emergy approach into sustainability and decoupling research, proposing a new insight into decoupling measurement with integrated quantitative modes, combing with developing new indicators, aiming towards a better understanding of the decoupling at a city level.

As shown in other developing and transition countries [21,22,44], decoupling in a transition city shows an erratic appearance. The trajectory of economic growth and environmental pressure shows absolute decoupling, while that of economic growth and resources utilization shows multi phases. Five new emergy-based indicators were developed and applied in this research for quantifying the city's sustainability and decoupling, which are the economic efficiency (EE), the environmental pressure (EP), the emergy-based five-year yield efficiency (FYE), the investment cost for decoupling (IfD), and the job-opportunities cost (JfD). In general, we could conclude that, along with the economic growth, the emergy-based economic efficiency has been improved and the environmental pressure has decreased during the past few decades, while the comprisable environmental protection investment decreased. Our study shows that in statistic, decoupling at a transition city level has impacts to local employment; however, even though the total job opportunities would be decreased along with the decoupling process, but the relative cost per unit remains almost at the same level. However, the outcomes of an isolated and methodology-oriented case study in Shenyang city only provide the primary understandings and implications to the policy making on decoupling; thus, a wider scale comparison between different cities should be carried out for more knowledge mining.

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Author Contributions

Liming Zhang contributed to data collection, data processing and draft paper; Bing Xue conducted the research and responsible for structural design, data analysis as well as paper revised; Yong Geng, Wanxia Ren and Chengpeng contributed to data analysis and paper revised.

Conflicts of Interest

The authors declare no conflict of interest.

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