Chin. Geogra. Sci. 2018 Vol. 28 No. 1 pp. 127–136
https://doi.org/10.1007/s11769-018-0935-9

Springer Science Press
www.springerlink.com/content/1002-0063

Ecological Network Analysis Quantifying the Sustainability of Regional Economies: A Case Study of Guangdong Province in China

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Abstract: To meet the challenge of sustainable development, sustainability must be made. Ecological network analysis (ENA) was introduced in this paper as an approach to quantitatively measure the growth, development, and sustainability of an economic system. The Guangdong economic networks from 1987 to 2010 were analyzed by applying the ENA approach. Firstly, a currency flow network among economic sectors was constructed to represent the Guangdong economic system by adapting the input-output (I-O) table data. Then, the network indicators from the ENA framework involving the total system throughput (*TST*), average mutual information (*AMI*), ascendency (*A*), redundancy (*R*) and development capacity (*C)* were calculated. Lastly, the network indicators were analyzed to acquire the overall features of Guangdong's economic operations during 1987–2010. The results are as follows: the trends of the network indicators show that the size of the Guangdong economic network grows exponentially at a high rate during 1987–2010, whereas its efficiency does not present a clear trend over its whole period. The growth is the main characteristic of the Guangdong economy during 1987–2010, with no clear evidence regarding its development. The quantitative results of the network also confirmed that the growth contributed to a great majority of the Guangdong economy during1987–2010, whereas the development's contribution was tiny during the same period. The average value of the sustainability indicator (α) of the Guangdong economic network was 0.222 during 1987–2010, which is less than the theoretically optimal value of 0.37 for a sustainable human-influenced system. The results suggest that the Guangdong economic system needs a further autocatalysis to improve its efficiency to support the system maintaining a sustainable evolvement.

Keywords: network analysis; regional economy; sustainability evaluation; ascendency; Guangdong Province of China

Citation: LIANG Jinshe, HU Ke, DAI Teqi, 2018. Ecological Network Analysis Quantifying the Sustainability of Regional Economies: A Case Study of Guangdong Province in China. *Chinese Geographical Science*, 28(1): 127–136. https://doi.org/10.1007/s11769-018-0935-9

1 Introduction

To meet the challenge of sustainable development, sustainability must be made (Kates and Clark, 1999; Clark and Dickson, 2003; Bettencourt and Kaur, 2011). To this end, several methods have been proposed. For example, the socio-ecological indicators method (Azar et al., 1996) estimates the sustainable situation of an area by constructing a system of socio-ecological indicators, and then calculating the index of the indicators. The ecological footprint (Wackernagel et al., 1999) judges an area's sustainable development state by calculating the ecological footprint of human activities and the ecological carrying capacity of the area. The emergy analysis method (Brown and Herendeen, 1996) measures the status of sustainable development of an area by converting the different types of emergy into the standard solar value, and evaluates the integration between human activities and natural environment (Brown and Ulgiati, 1997; Egilmez et al., 2013). Even though during

Received date: 2017-03-17; accepted date: 2017-06-16
Foundation item: Under the auspices of the Fundamental Research Funds for the Central Universities, China (No. 2015KJJCB30)
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the last two decades the methods above have been quickly applied to evaluate the sustainability of an area at local, regional, and global scales, none can identify the distinction between growth and development, which are two inherent processes in any system, from micro-organisms to the universe, and the both of them are closely related to the sustainability of the organized system (Ulanowicz, 1986). The development is an independent of the physical size of system from the perspective of the ecological economics. The increase of the physical size in the material or energy flow of economic activities is regarded as the economic growth, whereas the economic development is the improvement in the productive efficiency devoiced from the knowledge, technology, and the organizational ability (Daly, 1996). To acquire the sustainable state of a system, it is need to investigating the relationship between growth, development, and sustainability in the system evolvement.

The Ecological Network Analysis (ENA) model (Ulanowicz, 1986; 1997) is an approach to address the overall feature of a system by analyzing its network of medium flow (material, energy, information), with the functions such as, addressing a system's structure, describing the medium flow network of a system, and investigating the interaction between some individual components of a system (Ulanowicz, 1980; Fath and Patten, 1999; Fath et al., 2007; Borrett et al., 2014). In the field of the sustainability evaluation, the ENA approach has its advantages in aspects of separating the growth and development of a system, quantifying the contributions of the size and efficiency to the system evolvement, and measuring the sustainability state of a system. It has been used widely to evaluate the stability, health, efficiency and sustainability of ecosystems. In addition, it has been applied in fields such as urban metabolic systems (Zhang et al., 2009; 2014; Yang et al., 2014; Chen and Chen, 2015), social metabolism analyses (Dai et al., 2012; Zhang et al., 2012), landscape ecology (Saura et al., 2011; Bonacini et al., 2017), and systems of water resource in basins (Li et al., 2009; Li and Yang, 2011; Fang and Chen, 2015). More recently, the ENA approach has increasingly been applied in the theoretical and empirical analyses of economic systems. Templet (1999) adopted energy flow networks among the economic sectors of six developed countries and six developing countries to discuss the relationship between economic diversity, output (GNP), and development capacity. Goerner et al. (2009) concluded that network analysis and its related concepts can be used to provide a new narrative for the long term economic health and sustainability, because using the Gross Domestic Product (GDP) as a volume indicator, one is unable to distinguish between growth and development, or between a bubble economy and a resilient one. Kharrazi et al. (2013) applied the ENA approach to analyze six kinds of trade flow networks for economic resources: virtual water, oil, world commodity, OECD + BRIC commodity, OECD + BRIC foreign direct investment, and iron & steel. It appears that the trends of measured efficiency and redundancy of studied networks are demonstrated to be useful in reflecting a long term changes, while the trends in the robustness levels were found to exhibit similar behavior to an ecosystem in its early phase of development.

Guangdong Province's economy has been growing rapidly since the 1980s, and has recorded the biggest GDP of any province in China from 1989 onwards. While the GDP statistic, as a volume indicator, can partially describe the trends of a regional economy, it can not describe the regional economy's efficiency, health, and sustainability, which are important features that should be examined. This study applies the ENA approach to analyze the overall network features of the Guangdong economy during 1987–2010, and quantitatively measures the contribution of the growth and the development to its economic system evolvement. Firstly, using the I-O table data, the Guangdong economic system is represented as a multiple sector currency flow network. Then, the network indicators are calculated from 1987 to 2010 to address the overall features of the growth, development, and sustainability of the Guangdong economy. Finally, we discuss the results.

2 Materials and Methods

2.1 Data sources

The first step to applying the ENA approach is the construction of a flow network that represents the system of interest. To represent the economic system, this study uses the I-O table data to construct the currency flow network because the currency flow includes the most information of economic processes, such as goods, services, and value, *etc*. The economic I-O tables of Guangdong Province in 1987, 1990, 1992, 1995, 1997, 2000, 2002, 2005, 2007 and 2010 are used for constructing the currency flow network in those years. The tables come from the Statistics Bureau of Guangdong Province. The economic sectors of these I-O tables are not consistent in different years, such as: the tables for 1987, 1990, 1992, 1995 and 1997 are made up of 33 sectors, the table for 2000 consists of 40 sectors, and those for 2002, 2005, 2007 and 2010 consist of 42 sectors. For the needs of analysis and comparison, all I-O tables from 1987 to 2010 are adapted into a common form with six sectors: agriculture; industry; construction; TPT (transportation, post, and telecommunications); WHR (wholesale & retail, hotel, and restaurant); and other services. In addition, the export item is one sub-item of final-use item in the original structure of these I-O tables. In particular, we separate the export item from the final-use item, to satisfy the needs of constructing the flow network.

2.2 Construction of the network

In order to construct the currency flow network, we require four kinds of flows: inputs, outputs, internal flows, and losses. Here, we use the four kinds of data provided by the I-O model namely import data, export data, sectors matrix, and final-use data (excluding export) respectively, to represent the four kinds of path flows in the network analysis (Ulanowicz and Norden, 1990). The sectors in the I-O table are taken to refer to the nodes of the network. The currency flow in the I-O table is taken to refer to the flow medium of the network. Thus, the Guangdong economic system is represented by a six-sector currency flow network (Fig. 1).

2.3 Calculation of network indicators

2.3.1 Calculation of total system throughput

In the ENA framework, growth usually implies an increase and/or expansion, which may involve either a greater spatial extent, or the accretion of medium flow (material, energy, information). Growth is commonly quantified as any increase in the total system throughput (*TST*) of the medium flow network (Ulanowicz, 1986).

Defining T_{ij} as the medium flow from compartment i to compartment j. Then the sum of medium flows leaving compartment i during a time interval is represented as $T_{i.}(=\sum_j T_{ij})$, the sum of medium flows inputting into

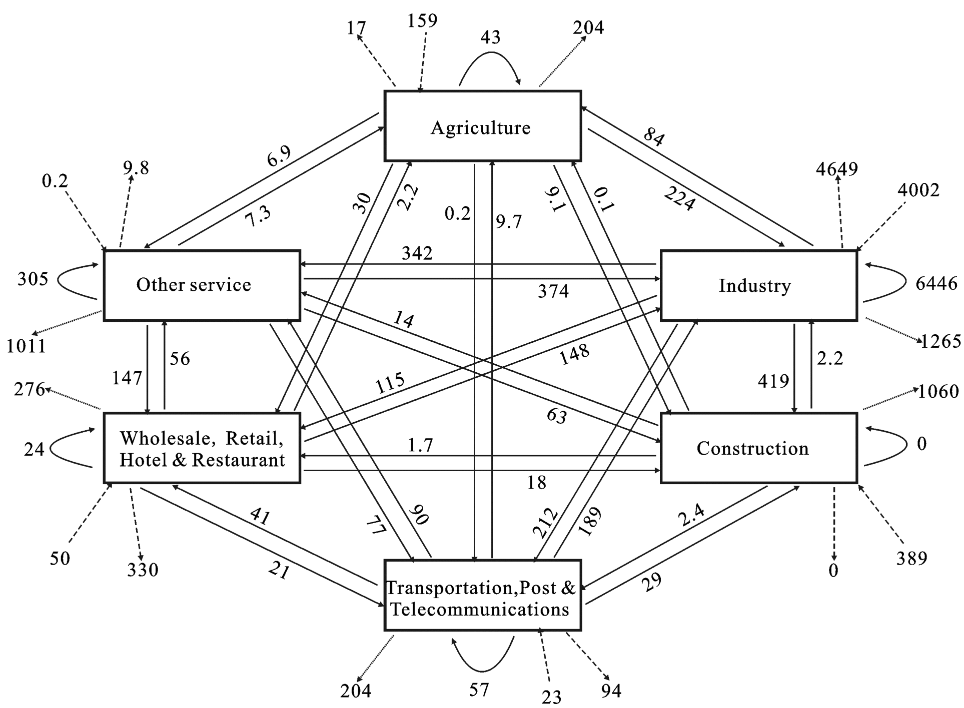

Fig. 1 Currency network flows among six economic sectors in 2010, Guangdong Province, China (Unit: 10^9 yuan (RMB)). The broken lines not originating from a box represent inputs from other systems; the broken lines not terminating in a box represent outputs to other systems; the dotted lines not terminating in a box represent final-use; the curve solid lines represent inputs from the sector itself; and other solid arrows represent currency flows among economic sectors

compartment j at the same time is represented as $T_{.j}(=\sum_i T_{ij})$, and the sum of all medium flows within the system is represented as $T_{..}(=\sum_{i,j} T_{ij})$. Thus, the *TST* can be expressed as shown in equation (1).

$$TST=\sum_{i,j} T_{ij}=T_{..} \tag{1}$$

Substituting the currency flow data among the Guangdong economic network during 1987–2010 into Equation (1), the *TST*s of the Guangdong economic network in those years are calculated. To avoid the situation in which the *TST* values in different years are influenced by the prices of those years, we convert all magnitudes of the *TST*s in different years into a constant-price of the year 1987. The constant-price *TST*s of the Guangdong economic network from 1987 to 2010 are listed in Table 1.

2.3.2 Calculation of average mutual information

In the ENA framework, development is defined as an improvement of organization and/or structure, which is an independent of the size of a system. The organizational efficiency of the system can be measured by the average mutual information (*AMI*) of the flow network (Ulanowicz, 1986).

Information is defined as a decrease in indeterminacy. Defining the probability of the occurrence of event i as $p(i)$. Then, the indeterminacy of event i is estimated as $h_i = -k \log p(i)$. Here, k defines the unit of information. The value of k is determined by the base of the logarithm. If this value is 2, then k is 1 'bit'. Under the condition that the natural logarithm is used, then k is 1 'nat'. Thus, the indeterminacy of the whole system can be expressed as in Equation (2).

$$H=\sum_i p(i)h_i=-k\sum_i p(i)\log p(i) \tag{2}$$

If one knows both the indeterminacy of event i, and the indeterminacy of event i when event j occurs, then the decrease in indeterminacy for event i induced by event j is given by Equation (3).

$$\begin{aligned}X(i|j)&=[-k\log p(i)]-[-k\log p(i|j)]=k\log(\frac{p(ij)}{p(i)p(j)})\\&=[-k\log p(j)]-[-k\log p(j|i)]=X(j|i)\end{aligned} \tag{3}$$

Equation (3) illustrates that the information for event i, given that event j occurs is equal to the information for event j, given that event i occurs. Therefore, this is considered the mutual information both i and j. The average mutual information (*AMI*) of the whole system can is given by Equation (4).

$$AMI=k\sum_i\sum_j p(ij)\log(\frac{p(ij)}{p(j)p(i)}) \tag{4}$$

In the ENA framework, event i refers to the medium flow leaving compartment i; event j refers to the medium flow input to compartment j; and event ij refers to the medium flow leaving compartment i and then input to compartment j. The probabilities of i, j, and ij are expressed as: $p(i)\frac{T_{i.}}{T_{..}}, p(j)\frac{T_{.j}}{T_{..}}, p(ij)\frac{T_{ij}}{T_{..}}$, respectively. Substituting these estimators into equations (2) and (4), yields equations (5) and (6), respectively.

$$H=-k\sum_{i,j}\frac{T_{ij}}{T_{..}}\log\left(\frac{T_{ij}}{T_{..}}\right) \tag{5}$$

$$AMI=k\sum_{i,j}\frac{T_{ij}}{T_{..}}\log\left(\frac{T_{ij}T_{..}}{T_{.j}T_{i.}}\right) \tag{6}$$

In Equation (5), H is the diversity of a system (Ulanowicz, 1986; 1997). In Equation (6), *AMI* is the average mutual information (*AMI*) of a system. According to the attribution of the logarithmic function, there is the relationship: $H \geq AMI \geq 0$, where the diversity (H) is the upper limit of the *AMI*. Here, *AMI* is the degree of the movement of the medium flow, which is restricted by the system structure. The more organized a system is, the more restrictive is the structure, and the more certain is the link of medium movement. The efficient is greater when an amount of the medium passes through an organized system, than when it passes through a less certain link. Therefore, *AMI* is a measure of the regular, orderly, coherent, and efficient behaviors of a system. An increase in *AMI* means an improvement in the organizational ability and efficiency (i.e., the development) of a system.

Substituting the currency flow data among the Guangdong economic network during 1987–2010 into equations (5) and (6), the H and *AMI* of the Guangdong economic network in those years are respectively calculated and listed in Table 1.

2.3.3 Calculation of ascendency, redundancy and development capacity

The product of *TST* and *AMI* is defined as ascendency (A) (Ulanowicz, 1986; 1997), which is expressed as shown in Equation (7). The ascendency (A), which combines with the activity and organization of the flow network, is a measure of the efficient part of a system.

$$A = TST \cdot AMI = \sum_{i,j} T_{ij} \log\left(\frac{T_{ij}T_{..}}{T_{.j}T_{i.}}\right) \tag{7}$$

The product of *TST* and H is defined as development capability (C) (Ulanowicz, 1986; 1997), which is expressed as shown in Equation (8). Since $H \geq AMI \geq 0$, therefore, $C \geq A \geq 0$. Thus, the development capability (C) is the upper limit of the ascendency (A).

$$C = TST \cdot H = -k\sum_{i,j} T_{ij} \log\left(\frac{T_{ij}}{T_{..}}\right) \tag{8}$$

The difference between the development capacity (C) and the ascendency (A) is defined as the overhead or redundancy (R) (Ulanowicz and Norden, 1990; Ulanowicz et al., 2009), which is expressed as shown in Equation (9).

$$R = C - A \tag{9}$$

The attribute of redundancy (R) is opposite to the ascendency (A), and reflects the inefficient part of a system. From an evolving perspective, the increasing proportions of ascendency (A) represents that the system is evolving to more efficiency and order. In contrast, the increasing proportion of redundancy (R) represents that the system is evolving to more inefficiency and disorder.

The values of A, C and R of the Guangdong economic network from 1987 to 2010 are respectively calculated according to equations (7) (8) (9), and are listed in Table 1.

2.3.4 Measurement of sustainability

Since the Equation (9), therefore the ascendency (A) and redundancy (R) of a network are opposing in their proportion, with $A/C + R/C = 1$. By the long-term observation for the natural ecological network (Ulanowicz et al., 2009), the experiment conclusion for the random networks (Morris et al., 2005), and the theoretical verification for the human-influenced network (Lietaer et al., 2009), it is indicated that a system can achieve a sustainable evolvement when the proportion of ascendency (A) and redundancy (R) maintained within a suitable A/R ratio range. Whereas, the system is not in a sustainable evolvement if the A/R ratio lies outside its suitable A/R ratio range (Fig. 2).

When the A/R ratio of a network is lower than its suitable range, the system is weakly constricted by its structure. Therefore, the system is lacking the organizational ability and the survival vitality. In this situation, an increase of the *AMI* will improve the A/R ratio, enhance the sustainability of the system. And a decrease of the *AMI* will reduce the A/R ratio, lead the system to evolve into stagnation or decline.

In turn, when the A/R ratio of a network is higher than its suitable range, the system is overly constricted by its structure. Therefore, the system is unstable and easy to collapse under any slight disturbance. In this situation, an increase of the *AMI* will improve the A/R ratio furtherly, lead the system to evolve into fragile. And a decrease of the *AMI* will reduce A/R ratio, enhance the sustainability of the system.

Table 1 The network indicators value of the six economic sectors network, Guangdong Province, China

Year	1987	1990	1992	1995	1997	2000	2002	2005	2007	2010
TST (10^9 yuan (RMB))	308	421	678	1236	1548	2103	2547	3947	5477	6164
H (bits)	2.244	2.201	2.124	2.098	2.028	1.986	1.984	1.843	1.784	1.883
AMI (bits)	0.437	0.378	0.447	0.361	0.460	0.504	0.477	0.456	0.462	0.453
A (10^9 yuan (RMB)•bits)	135	159	303	446	713	1061	1214	1802	2532	2789
R (10^9 yuan (RMB)•bits)	556	767	1137	2147	2426	3117	3839	5473	7237	8816
C (10^9 yuan (RMB)•bits)	691	927	1440	2592	3138	4177	5053	7275	9769	11605
$\alpha = A/C$	0.195	0.172	0.211	0.172	0.227	0.254	0.240	0.248	0.259	0.240

Notes: The *TST*, H, *AMI*, A, R, C, and α refer to the total system throughput, diversity, average mutual information, ascendency, redundancy, development capacity, and sustainability indicator of the economic network, respectively. The network indictors related to price were converted to constant price of 1987

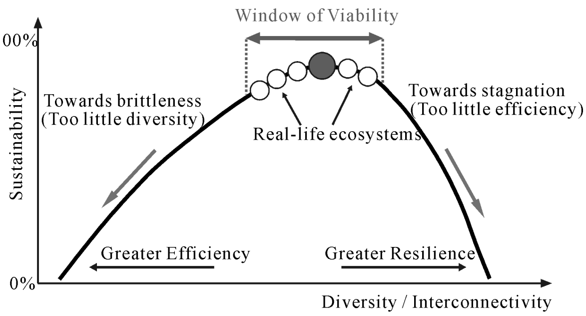

Fig. 2 Sustainability of flow networks as a function of the trade-off between efficiency and redundancy, Source: Lietaer et al., 2009

Thus, one can judge the sustainability state of a system by analyzing the A/R ratio, and know whether the system is evolving to sustainable by analyzing the change of the *AMI*. Since this A/R ratio possibly locates in the range of [0, +∞), it is not convenient for analysis and discussion. Thus, researchers often use $\alpha = (A/C)$, with the range of [0, 1], instead of the A/R ratio, for the purposes of convenient discussion.

It is noticed that even though the ascendency (A) is affected by the *TST*, the *TST* has no influence on the measurement of sustainability. Because A, R, and C, all of them consist of the *TST* factor, with the equations: $A = TST \cdot AMI$, $C = TST \cdot H$ and $R = TST \cdot (H - A)$. Therefore, the *TST* is unable to affect the ratio between A, R, and C.

2.4 Quantification of growth and development

If $V = xy$, V is determined equally by factors x and y. The relative contributions of factors x and y to V are shown in Equation (10).

$$x_{effect} = y_0 \Delta x + \frac{1}{2} \Delta x \Delta y$$
$$y_{effect} = x_0 \Delta y + \frac{1}{2} \Delta x \Delta y \quad (10)$$

It is known that the ascendency (A) is determined by the total system throughput (*TST*) and the average mutual information (*AMI*): $A = TST \cdot AMI$. Thus, the contributions of the *TST* and *AMI* to A of the Guangdong economic network from 1987 to 2010 are calculated according to Equation (10), and listed in Table 2.

3 Results Analysis

3.1 *TST* trend and analysis of growth

Fig. 3 shows the constant-price *TST* trend of the Guangdong economic network during 1987–2010. The constant-price *TST* of the network increased in exponentially, from 3.077×10^{11} yuan (RMB)/yr in 1987, and increasing to 6.164×10^{12} yuan (RMB)/yr in 2010 (in constant prices of 1987), with an annual average rise rate of 13.9% over the study period. The network *TST*'s increase signals that the scale of the system has grown to some degree in the ENA framework. The exponential trend of the *TST* in the Guangdong economic network from 1987 to 2010, means that the size of Guangdong economic system kept a continuous growth in this period from the perspective of ENA. This result coincides with the conclusion of Templet (1999), who found that in the process of GNP rising, the *TST* of the energy networks in the studied six developing countries all exhibited a rising trend, while the studied six developed countries didn't.

3.2 *AMI* trend and analysis of development

Fig. 4 shows that the *AMI* trend of the Guangdong economic network during 1987–2010 is complex, has multiple fluctuations, and does not have a clear trend. The *AMI* value of the network is the measure of the system's efficiency in the ENA framework. The fact that the *AMI* of the network did not display a clear trend over the study interval, means that the efficiency of the Guangdong economy has not achieved a higher level. The evidence of development in the Guangdong economic system is not clear from the ENA perspective.

Table 2 Contribution of the total system throughput (*TST*) and average mutual information (*AMI*) to ascendency (A) in six economic sectors network, Guangdong Province, China

Time interval	1987–1990	1990–1992	1992–1995	1995–1997	1997–2000	2000–2002	2002–2005	2005–2007	2007–2010	Total of 1987–2010
TST's contribution	187%	74%	158%	48%	77%	142%	111%	96%	122%	98%
AMI's contribution	–87%	26%	–58%	52%	23%	–42%	–11%	4%	–22%	2%

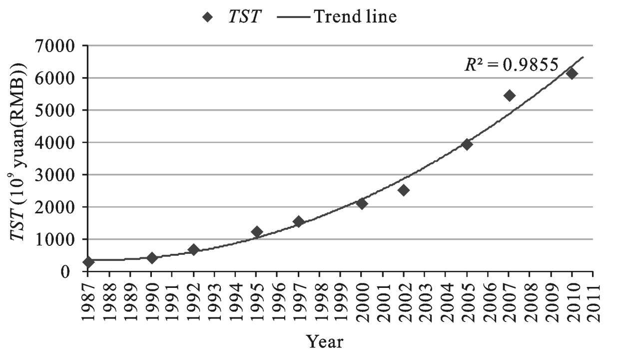

Fig. 3 The total system throughput (*TST*) trend line in the six economic sectors network of Guangdong Province during 1987–2010

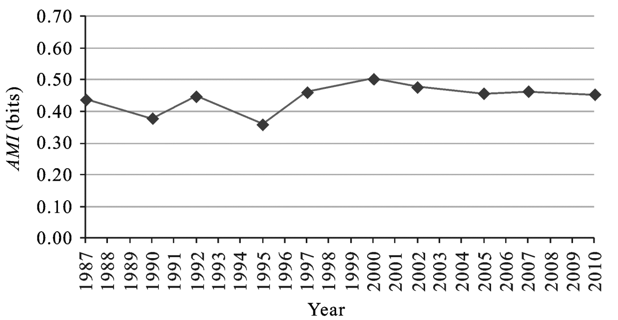

Fig. 4 The average mutual information (*AMI*) values in the six economic sectors network of Guangdong Province during 1987–2010

3.3 Sustainability analysis

Fig. 5 shows that both the ascendency (*A*) and the development capacity (*C*) of the Guangdong economic network increased exponentially during 1987–2010. In the ENA framework, the ascendency (*A*) of a system is affected by the combination of *TST* and *AMI*, and the development capacity (*C*) is affected by the combination of *TST* and diversity (*H*). The change of *A*, *C*, *TST*, *AMI*, and *H* during 1987–2010 in Table 1, indicates that the increase of the ascendency (*A*) and the development capacity (*C*) are primarily due to the *TST* increasing rapidly during this period, whereas the *AMI* and *H* remained largely unchanged. This result implies that even though the Guangdong economic system grew exponentially during 1987–2010, it did not achieve a higher level of development from the ENA perspective. The contribution of *TST* and *AMI* to the ascendency (*A*) (Table 2) further confirms that the *TST* contributed to about 98% of the ascendency (*A*) of the Guangdong economic network during 1987–2010, whereas the *AMI* contributed only 2% during the same period. This implies that during 1987–2010, the growth and the development of the Guangdong economic system were 98% and 2%, respectively.

Fig. 5 shows that the α value of the Guangdong economic network presents a complicated fluctuation during 1987–2010, with a small degree of increase from the perspective of the whole period. The average value of α is 0.222 during 1987–2010.

Ulanowicz et al. (2009) concluded that a system can maintain optimal sustainability when the $\alpha = (A/C)$ is close to a value of 0.4596. This conclusion came from the observation of the natural ecological network. But the processes of an economic network, as a human-influenced network, are more complicated than the processes of the natural ecological network. For example, the currency flow can bidirectionally move between compartments (nodes) in an economic network, whereas in a natural ecological network, energy can only flow directly from a rabbit to a tiger, it can't flow in the opposite direction (Huang and Ulanowicz, 2014). Lietaer et al. (2009) concluded that a human-influenced complicated network could maintain an optimal sustainable state when *C* is twice the times as *A*, which means that the optimal value of α should be 0.33. Morris et al. (2005) constructed the thousands of random networks varying in size, and observed that a great amount of α showed a cluster to 0.37: a value closed to the asymptotic line of 1/e. In empirical study cases, Kharrazi et al. (2013) obtained the average α value of the global virtual water trade network for 227 countries is 0.181 during 1896–2001; the average α value of the global oil trade network for 137 countries is 0.199 during 2007–2011; and the average α value of the global iron & steel trade network for 199 countries is 0.127 during 1962–2011.

Fig. 6 shows that the average α value of the Guangdong

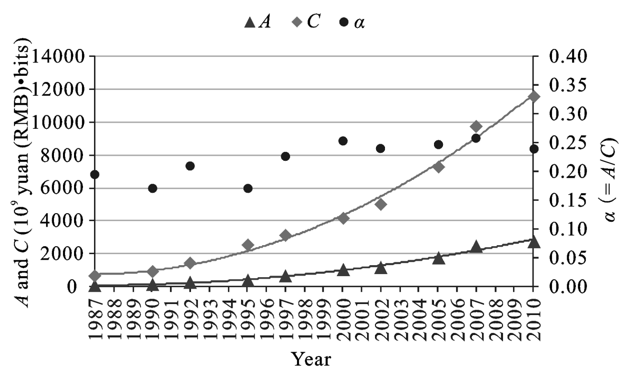

Fig. 5 The ascendency (*A*), development capacity (*C*) and sustainability indicator (α) in the six economic sectors network of Guangdong Province during 1987–2010

economic networks during 1987–2010 is 0.222. This value is similar with the empirical value of α in the global oil trade network for 2007–2011 and global virtual water trade network for 1896–2001, and has a big gap with the theoretically optimal value of 0.37 (or 0.33) for a sustainable human-influenced network. This result means that the ascendency (A) of the system is lower than what has been proposed in the optimal sustainable condition. In the ENA framework, the system in this condition is weakly constricted by its structure and lacks of organizational efficiency. The system needs to improve its efficiency in order to maintain a sustainable evolvement. If this theoretically optimal magnitude is suitable for the economic system, it would appear that the Guangdong economic system needs a further autocatalysis to improve its efficiency to support the system maintaining a sustainable evolvement.

4 Discussion

During 1987–2010, the Guangdong Province's economy shown a rapid growth, with a high GDP annual growth rate of 13.69%, and was recorded the biggest GDP province in China in 1989. However, the Guangdong economy also exhibited some features of extensive growth in the same period. For example, the Guangdong economy's growth is highly dependent on the increase of capital investment. Its capital formation rate (= gross capital formation/GDP) maintained at a high percentage range of 32.80%–44.34% during 1987–2010. And its gross capital formation of constant-price during 1987–2010 received a high annual growth speed of 13.52% that is close to GDP's annual growth speed of 13.69% in the same period. It reflects that the Guangdong economy is lacking of efficiency in partly. In addition, the Guangdong economy strongly relies on its export and import trade. During 1990–2010, its foreign trade degree of dependence (= total value of imports and exports / GDP) was up to 136% at averagely, which is far higher than the world average of 41.7% in 2000 year. In specially, of the import and export trade in the period of 1990–2010, more than 65% belonged to the processing-trade industry. From the aspect of product value chain, the manufacture of product lies in the lowest value-added chain. This also reflects that the Guangdong economy is lacking of efficiency.

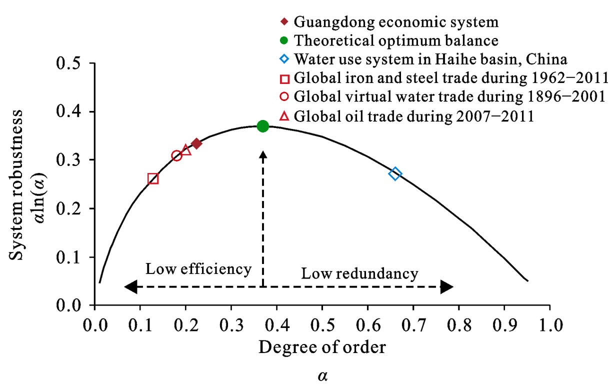

Fig. 6 The illustration of average α for 1987–2010 in Guangdong economic network, and comparison to the α in theoretically optimum balance and empirical α values in some other human-influenced networks. The α in theoretically optimum balance takes the magnitude of 0.37. The α values in the global oil trade network, global virtual water trade network, global iron & steel trade networks are derived from (Kharrazi et al., 2013), and the α value of water use network in Haihe basin of China is derived from (Li and Yang, 2011)

The result of this study realized that the Guangdong economic network during 1987–2010 is far from the optimal sustainable state. The aspect that the Guangdong economy lacks efficiency is indicated by employing the ENA approach. In this study, the ENA approach showed its insight into the economic efficiency and sustainability, when a lot of extensive growth did exist among Guangdong economy and GDP indicator was unable to reflect the aspect of economic health. The ENA approach provides a new narrative for the long term economic health and sustainability. It can get the trend of size and efficiency in the evolving process of a system, and can measure the contribution of growth and development to the system. Also, it can catch up the sustainability state of a system, and know whether the efficiency of the system is higher than, or lower than, or stay in its suitable range. This approach is a useful tool to measure the overall feature of a system.

5 Conclusions

Thus far, we have quantitatively measured the growth, development, and sustainability of the Guangdong economic system from 1987 to 2010 by employing the ENA approach. The overall features of the Guangdong economy during 1987–2010 are addressed by analyzing the networks indictors.

The trends of the network indicators show that the *TST* of the Guangdong economic network increased exponentially at a high rate during 1987–2010, which implies that the size of the Guangdong economic system grew rapidly during this period. On the other hand, the *AMI* trend of the network is complicated, and did not display a clear trend over the whole period. From an overall view, growth was the main characteristic of the Guangdong economy during 1987–2010, with no clear evidence regarding its development. The quantitative result of the network also confirmed that the *TST* contributed about 98% to the ascendency (*A*) during 1987–2010. In contrast, the contribution of the efficiency was only 2% during the same period. From the ENA perspective, this result implies that the growth and the development attribute 98% and 2%, respectively, to Guangdong economy during 1987–2010. The sustainability indicator: α of the Guangdong economic network had an average value 0.222 during 1987–2010, which is less than the theoretically optimal magnitude of 0.37 for a sustainable human-influenced network. If this theoretical value is a suitable ratio for the economic system, the results suggest that the Guangdong economic system need a further autocatalysis to improve its efficiency to support the system maintaining a sustainable evolvement.

Acknowledgements

The authors are grateful to the anonymous reviewers for their helpful comments and suggestions, the Statistics Bureau of Guangdong Province for their kindly help in the I-O data.

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