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Ecological Network Analysis of the Economic Efficiency Based on Input-output Tables: A Case Study of Tianjin City, China

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Abstract: *The ecological network analysis (ENA) method is introduced to assess the overall features of growth, development, and sustainability in the economic system at the city level, and is then applied to Tianjin City in the Beijing-Tianjin-Hebei metropolitan area of China. The economic network of Tianjin City from 1992–2017 is constructed and analyzed to describe the size, efficiency, relicense, and sustainability of system evolvement. The results are as follows (1) the long-term trend of the size indicator indicates that Tianjin City's economic network grows exponentially at a high rate during the study period. During 1992-1997, the economy efficiency of Tianjin City improved, while its resilience declined. Between 1997 and 2017, there was no significant change in economic efficiency and resilience. The size growth is the main characteristic of the Tianjin economy during 1992-2017. (2) The quantitative result of the network analysis confirms that the growth in size and the development in efficiency contribute 59% and 41% to the Tianjin economy during 1992–2017, respectively. (3) The average value of the sustainability indicator (α) is 0.195 during the overall period, which is far less than the theoretical sustainability optimal value of 0.37. If the theoretical value of 0.37 is a suitable ratio for the human-influenced system, it would appear that the Tianjin economy needs to improve its efficiency to maintain a sustainable evolvement.*

Keywords: *ecological network analysis; economic system; efficiency; resilience; sustainability; Tianjin City*

1. Introduction

To meet the challenge of sustainable development, sustainability must be made[1-3], and to this end, several methods have been proposed. For example, the socio-ecological indicators method[4] estimates the sustainable situation of an area by constructing a socio-ecological indicator set and then calculating the index of all indicators. The ecological footprint[5] estimates 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[6-7] measures the sustainable development status of an area by converting all kinds of emergy in the area into a standard solar value.

In an evolving system, both growth and development are inherent two processes, and closely related to the sustainability of the system[8]. The sustainability assessment of an organized system is necessary to investigate the relationship between the growth and development, as well as the efficiency and resilience of the system[9]. And an organized system's self-organization ability is composed of two interacting aspects: ascendency and resilience[10]. The ascendency represents the orderly, coherent, and efficient part of the system, reflecting the efficiency of the system; while the resilience represents the disorder, incoherence, and inefficient part of the system, reflecting the antiinterference ability of the system. From the perspective of system evolution, when the proportion of ascendency and resilience is maintained within a suitable ratio, the system can achieve sustainable evolvement. A system with too low ascendency or resilience is unsustainable. If the ascendency proportion is lower than the suitable ratio (the efficiency is too low), the system will evolve to stagnation and decline. In turn, if the ascendency proportion is higher than the suitable ratio (the resilience is too low), the system will tend to be unstable and fragile.

The ecological network analysis (ENA) model has the advantage of describing the network structure, the transform of medium flow, and the interaction relationship between the components in the system[11-13]. Within the ENA framework, when a system's medium flow network (material, energy, or information) is constructed, the sustainability of the system can be measured by assessing the balance of both the efficiency indicator and resilience indicator of the flow network[14], and the overall feature of ascendency can be quantified by separating the growth and the development in the flow network[10, 15]. The ENA approach has been used widely to evaluate ecosystems' stability, health, efficiency, and sustainability[16]. In addition, it has been applied in fields such as urban metabolic systems[17-18], social metabolism analyses[19-20], landscape ecology[21-22], and water resources system in basins[23-24]. More recently, the ENA approach has increasingly been applied in theoretical and empirical analyses of economic systems. Yang *et al.* (2016)[25] applied the ENA approach to estimate the transferred $PM_{2.5}$ emissions through 15 economic sectors in Beijing City of China. Tian *et al*. (2022)[26] combined the economic sector input-output (I-O) model and the industrial waste metabolic model to explore the transferred industrial waste emissions between economic sectors in Guangdong Province of China. Templet (1999)[27] adopted energy flow networks of economic sectors for six developed countries and six developing countries to discuss the relationship between economic diversity, output (GNP), and development capacity. Goerner *et al.* (2009)[28] concluded that an ENA and its related concepts can be used to provide a new narrative for long-term economic health and sustainability. Furthermore, they concluded that the gross domestic product (GDP), as a volume indicator, is unable to distinguish between growth and development, or between a bubble economy and a resilient economy. Kharrazi *et al*. (2013)[29] applied the ENA approach to analyze six kinds of trade flow networks of economic resources: virtual water, oil, world commodity, OECD + BRIC commodity, OECD + BRIC foreign direct investment, and iron and steel. The authors demonstrated that trends in the measured efficiency and resilience of the networks reflect long-term changes, and the trend in the level of robustness exhibits similar behavior to an ecosystem in its early phase of development.

Tianjin City is one of the four municipalities directly under the Central Government in China and an important node of the Beijing-Tianjin-Hebei metropolitan area. It is not only a hub city for railway transportation, but also a major sea outlet in the Beijing-Tianjin-Hebei region. The city's industrial composition is relatively complete, and various import and export industries have been relatively well developed. Thus the economic flow data of various industries are typical, which provides a foundation for building a flow analysis framework.

2. Materials and methods

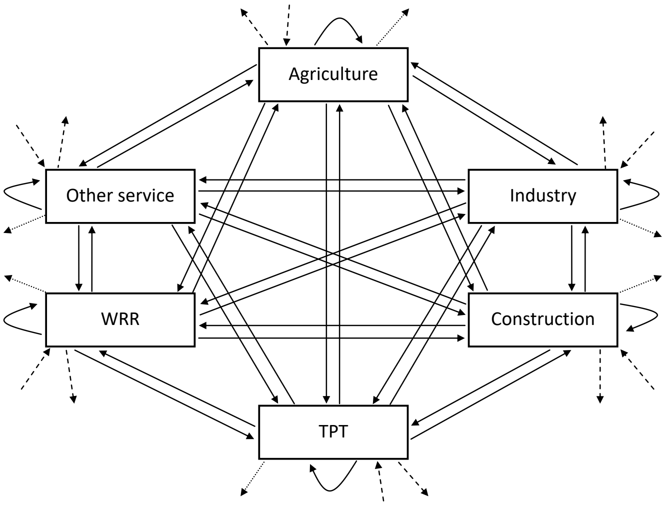
2.1. Data sources

The initial phase in the application of the ENA methodology entails the development of a flow network that encapsulates the system under study. This research leverages the Input-Output (I-O) model of the economic sector to delineate a monetary flow network, which serves as a proxy for the economic system. The rationale for this choice is that monetary flows encapsulate a wealth of information on economic transactions, encompassing goods, services, and value, among other economic activities.

To this end, the economic I-O tables for Tianjin City from the years 1992, 1997, 2002, 2007, 2012, and 2017 are utilized to construct the corresponding currency flow networks. These I-O tables are sourced from the "Tianjin Statistical Yearbook," a publication of the National Bureau of Statistics of China. It is noteworthy that the economic sectors delineated in these I-O tables vary across different years; for instance, the 1992 table comprises 33 sectors, the 1997 table includes 40 sectors, and the tables for the subsequent years—2002, 2007, 2012, and 2017—each consist of 42 sectors. In the interest of facilitating analysis and comparative studies, all I-O tables spanning from 1992 to 2017 have been standardized into a uniform structure that encompasses six sectors: agriculture; industry; construction; transportation, post, and telecommunications (TPT); wholesale and retail, hotel, and restaurant (WHR); and other services. Additionally, exports, which were initially categorized as a sub-item within the final-use data of the I-O model, have been reclassified as a distinct entity. This reconfiguration of the I-O model provides a coherent framework conducive to the construction of the flow network.

2.2. Construction of the network

To construct the medium flow network of an economic system, it is imperative to identify four distinct types of flows: inputs, outputs, internal transactions, and losses[30]. Here, we harness the quartet of data elements furnished by the Input-Output (I-O) model, namely import data, export data, the inter-sectoral transaction matrix, and final-demand data (with the exclusion of export data), to symbolize the respective directional flows within the network analysis framework. The individual sectors within the I-O model are construed as the nodal points of the network, while the monetary transactions captured by the I-O model serve as the medium of flow for the network. Consequently, the economic system of Tianjin City is depicted as a currency-based flow network comprising six sectors (**Fig 1**).



Note: (a) TPT refers to transportation, post, and telecommunications; WHR refers to wholesale and retail, hotel, and restaurants. (b) 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 items; the curved solid lines represent inputs from the sector itself; other solid arrows represent currency flows among economic sectors.

Figure 1: Currency network flows among six economic sectors, Tianjin City

2.3. Calculation of network indicators

2.3.1. Calculation of total system throughput

Within the ENA paradigm, the concept of system growth typically signifies an augmentation and/or proliferation, potentially manifesting as an expanded spatial distribution or an intensification of the medium flow's accumulation (encompassing material, energy, and information). The metric commonly employed to quantify growth is the escalation in the Total System Throughput (*TST*), which represents the aggregated flow of the medium within the network[10].

Define 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 flow input to 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 $T_{..}(=\sum_{i,j} T_{ij})$. Therefore, the *TST* can be expressed as shown in equation (1):

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

2.3.2. Calculation of average mutual information

Within the ENA framework, the development of a system is articulated as an enhancement in the organizational sophistication and/or structural integrity, which is conceptualized as being decoupled from the system's magnitude. The metric of organizational efficiency within the system is ascertained through the computation of the Average Mutual Information (AMI) of the constituent flow network[10].

Information is defined as a decrease in indeterminacy. Define 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 on 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 overall 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 for both *i* and *j*. The average mutual information (*AMI*) of the overall system 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 $p(i)\frac{T_{i.}}{T_{..}}, \quad p(j)\frac{T_{.j}}{T_{..}}, \quad p(ij)\frac{T_{ij}}{T_{..}}$, respectively. Substituting these estimators into equations (2) and (4) yields equations (5) and (6), respectively:

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

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

In equation (5), *H* denotes the diversity index of a system, which quantifies the variability and richness of its components. In Equation (6), *AMI* represents the Average Mutual Information, a metric that captures the average level of shared information among the system’s elements. The application of the logarithmic function establishes the hierarchical relationship $H \geq AMI \geq 0$, where diversity (*H*) is identified as the upper boundary for *AMI*. Here, *AMI* is construed as the extent of medium flow dynamics within the system, inherently constrained by the structural attributes of the system. The greater the organizational complexity of a system, the more rigid its structural framework, and consequently, the more predictable the pathways of medium flow. The passage of medium through a highly organized system is characterized by greater efficiency compared to its traversal through a system with less defined connectivity. Consequently, *AMI* serves as an index of the system’s regularity, orderliness, coherence, and operational efficiency. An increment in *AMI* signifies an enhancement in the system’s organizational capacity and efficiency, which is indicative of developmental progress.

2.3.3. Calculation of ascendency, resilience, and development capacity

The product of *TST* and *AMI* is defined as the ascendency (*A*)[10, 15], , which is expressed as shown in equation (7). Ascendancy (*A*) serves as an integrative indicator, encapsulating both the activity and the organizational attributes of the flow network, thereby quantifying the system’s efficient operational capacity.

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

The product of *TST* and *H* is defined as the development capability (*C*)[10, 15], which is expressed as shown in equation (8). Given $H \geq AMI \geq 0$, we have $C \geq A \geq 0$. Thus, the development capability (C) is the upper limit of the ascendency (A).

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

The difference between the development capacity (C) and ascendency (A) is defined as the overhead or resilience (R)[14, 30], with its formulation presented in Equation (9). Resilience (R), which is antithetical to the ascendency (A), serves as a metric for the system's inefficiency, delineating the unexploited potential and the capacity for internal reorganization in the face of perturbations.

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

Within the ENA framework, the ascendency (A) is recognized as a metric indicative of a system's progression toward enhanced efficiency and structural orderliness. Conversely, the resilience (R) is characterized as a measure of a system's tendency toward inefficiency and disarray. During the evolutionary trajectory of a system, the ascendency (A) and resilience (R) represent countervailing forces. A scenario where the ascendency (A) is suboptimal and the resilience (R) is excessive suggests a system that is minimally constrained by its structural framework, thereby exhibiting excessive disorder and a deficiency in the vitality and organizational capacity essential for sustenance. Under such conditions, the ecosystem is prone to stagnation or regression. Conversely, an overabundance of the ascendency (A) coupled with a dearth of the resilience (R) indicates a system that is rigidly bound by its structural constraints, rendering it overly brittle and susceptible to collapse upon encountering even minor perturbations. From a holistic standpoint, a system can sustain its evolution when the equilibrium between the ascendency (A) and resilience (R) is maintained within an optimal ratio range, as depicted in Figure 2. Should this equilibrium be disrupted, the system is considered to be in a state of disequilibrium, thereby undermining its capacity for sustainable evolution. Therefore, the analysis of the interplay between a system's ascendency (A) and resilience (R) provides a critical tool for assessing its sustainability.

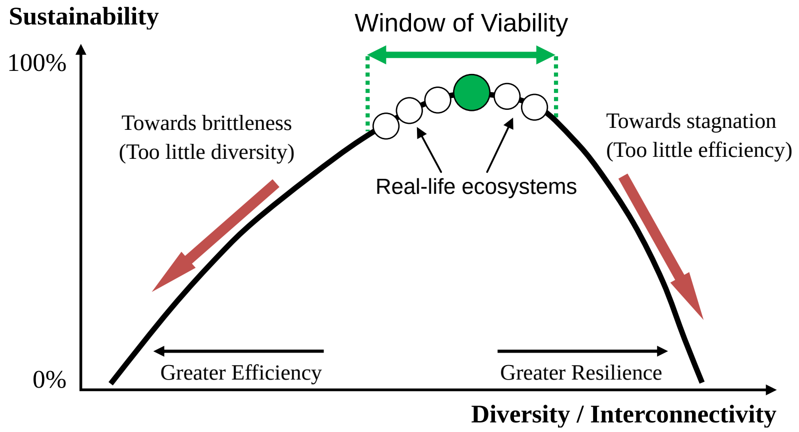


Figure 2: Sustainability of flow networks as a function of the trade-off between efficiency and resilience. Source: (Lietaer et al., 2009)

2.4. Quantification of growth and development

Given the equation $V = xy$, the variable V is posited to be influenced equally by the constituent factors x and y. The proportional contributions of these factors to the determination of V are articulated within the framework of equation (10):

$$\begin{aligned} x_{effect} &= y_0\Delta x + \frac{1}{2}\Delta x\Delta y \\ y_{effect} &= x_0\Delta y + \frac{1}{2}\Delta x\Delta y \end{aligned} \tag{10}$$

The ascendency (A) is ascertained through the synergistic influence of the total system throughput (TST) and the average mutual information (AMI), as articulated by the multiplicative relationship A =

$TST \cdot AMI$. Consequently, the respective contributions of *TST* and *AMI* to the ascendancy (A) within the economic network of Tianjin City, spanning the period from 1992 to 2017, are quantifiable by employing equation (10).

3. Results and Discussion

3.1. Economy growth feature

By substituting the monetary flow data from Tianjin City's economic network, encompassing the timeframe 1992 to 2017, into Equation (1), the *TST* values for the network are derived. To mitigate the potential confounding effects of nominal price fluctuations on the inter-annual *TST* values, a conversion to a constant price basis of 1992 is executed utilizing the GDP deflator. The resultant constant-price *TST* values for Tianjin City's economic network are systematically presented in **Table 1**.

Table 1: Network indicator in the six-sector network of the Tianjin economy for the period 1992–2017

Year	1992	1997	2002	2007	2012	2017
TST (10^9 RMB)	238	449	784	1458	2600	2332
AMI (nats)	0.125	0.410	0.473	0.455	0.553	0.458
H (nats)	1.736	2.036	2.120	2.112	2.170	2.268
A (10^9 RMB•nats)	30	184	371	663	1439	1069
C (10^9 RMB•nats)	414	915	1661	3080	5643	5288
R (10^9 RMB•nats)	384	731	1290	2417	4205	4219
$\alpha = A/C$	0.072	0.201	0.223	0.215	0.255	0.202

Note: The network indicators related to price are converted to a constant price of 1992.

The temporal trajectory of the constant-price *TST* for Tianjin City's economic network, as depicted (**Fig 3**), exhibits a pronounced upward trend. The *TST* values escalated exponentially from 238 billion RMB in 1992 to 2332 billion RMB in 2017, when measured in terms of 1992 prices, signifying a substantial annual compound growth rate of 16.42% throughout the period under investigation. Within the ENA framework, such an escalation in *TST* is indicative of an expansion in the system's scale. A holistic assessment of the *TST*'s exponential progression from 1992 to 2017 within Tianjin City's economic network corroborates the sustained augmentation of the system's magnitude over the specified interval.

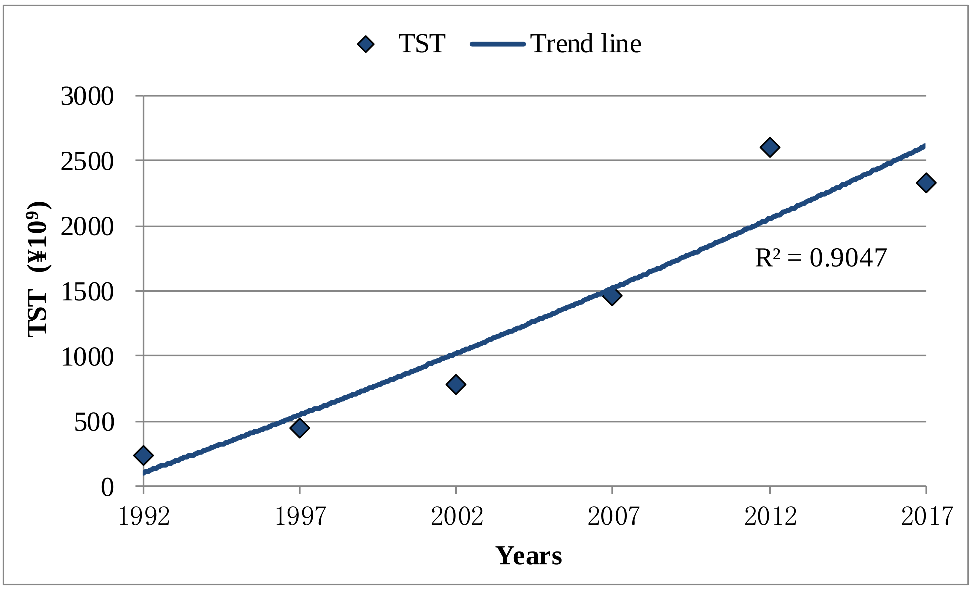


Figure 3: The TST trend line in the six-sector network of the Tianjin economy for the period 1992–2017

From a longitudinal perspective, the expansion of *TST* within Tianjin City's economic network aligns with the seminal findings of Templet (1999)[27], whose research postulated that an escalation in GNP was correlated with a positive trend in the *TST*s of energy networks across the six surveyed developing nations. In contrast, such a trend was not observed in the energy networks of the six developed countries examined in the study.

3.2. Economy efficiency and resilience feature

By incorporating the monetary flow data of Tianjin City's economic network for the duration of the study into Equations (5) and (6), the respective annual values of *H* and *AMI* for the network are computed, as detailed in **Table 1**.

The trajectory of the *AMI* within Tianjin City's economic network from 1992 to 2017 is characterized by complexity and lacks uniformity across the entire study period, exhibiting intermittent fluctuations during distinct intervals (**Fig 4**). The observed fluctuations in the *AMI* of Tianjin City's economic network are indicative of underlying variations in economic efficiency. The lowest *AMI* values in 1992 suggests a phase of diminished efficiency within the Tianjin economy, which corresponds to the Asian economic recession that emerged in the early 1990s. Conversely, the highest *AMI* values in 2012 denotes a period of heightened economic efficiency, aligning with the robust economic growth that Tianjin City experienced subsequent to the 2008 Beijing Olympic Games. It is noteworthy that a decrement in *AMI* was recorded in 2017 (**Fig 4**), mirroring a similar decline observed in *TST* for the same year (**Fig 3**). From the vantage point of ENA, the observed decline in both the magnitude and efficiency of Tianjin's economy in 2017 may be construed as an indicative signal. A plausible explanation for this phenomenon could be the incipient impact of the "housing restriction policies" implemented in China during that timeframe. The Input-Output (I-O) data corroborate a significant reduction in the flow within Tianjin City's construction sector from 2012 to 2017, which, in turn, had a cascading effect on the industrial sector's flow and the import flow of the construction sector itself.

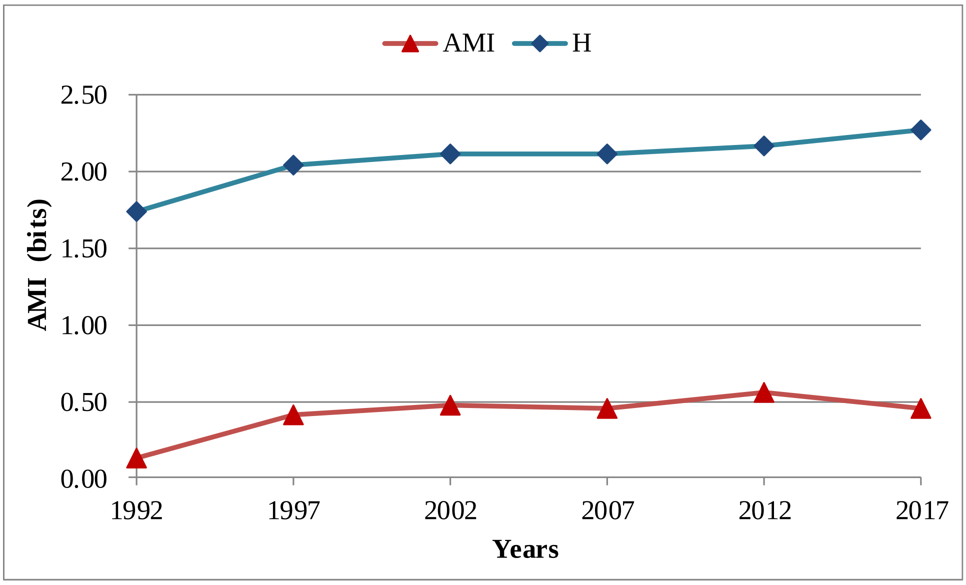


Figure 4: The AMI values in the six-sector network of the Tianjin economy for the period 1992–2017

When examining the temporal dynamics of *AMI* and *H* indices within the economic network of Tianjin City from a longitudinal perspective, a pronounced shift is observed between 1992 and 1997. Specifically, the rate of increase in *AMI* exceeds that of *H*, suggesting an enhancement in economic efficiency coupled with a concomitant reduction in resilience during this period. Post 1997, the indices exhibit a period of relative stability, with neither *AMI* nor *H* undergoing significant fluctuations, thereby indicating a period of equilibrium in both efficiency and resilience from 1997 to 2017. (**Fig 4**).

The consistent elevation of *AMI* values from 1997 to 2017 relative to those in 1992 suggests a quantifiable improvement in the network's efficiency, indicating that Tianjin City's economic system has attained a degree of developmental progression during the latter decade. Nonetheless, it is imperative to note that the magnitude of this increase is less pronounced compared to the escalation observed in the *TST*.

3.3. Quantification of economy efficiency

The quantitative metrics of *A*, *C*, and *R* for Tianjin City’s economic network, spanning the years 1992 to 2017, have been meticulously determined employing equations (7), (8), and (9), respectively. A compilation of these computed results is presented in **Table 1**.

An exponential augmentation is observed in both the ascendancy (*A*) and development capacity (*C*) of Tianjin City’s economic network throughout the 1992–2017 period (**Fig 5**). Within 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 changes in *A*, *C*, *TST*, *AMI*, and *H* for the period 1992–2017 in **Table 1** show that the increase in the ascendency (*A*) and development capacity (*C*) were primarily due to the rapid increase in *TST* during this period. This result indicates that growth is the main characteristic of the Tianjin economy during 1992-2017.

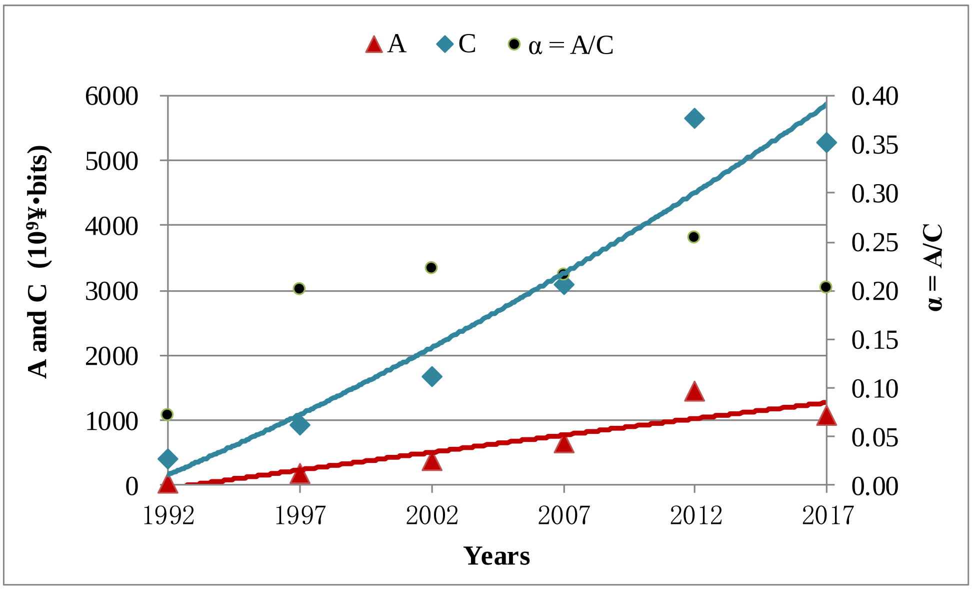


Figure 5: A, C, and α of in the six-sector network of the Tianjin economy for the period 1992–2017

To further characterize the growth and development of Tianjin City’s economic network quantitatively during the study period, we calculate the contributions of *TST* and *AMI* to *A* in the network using equation (10). The results are shown in **Table 2**. The contributions of *TST* and *AMI* to the ascendency (*A*) (**Table 2**) confirm that *TST* contributes about 59% to the ascendency (*A*) of Tianjin City’s economic network from 1992 to 2017, whereas *AMI* contributes only 41% during the same period. Thus, the growth in network size and the development in network efficiency contribute 59% and 41% to the Tianjin economy during 1992–2017, respectively.

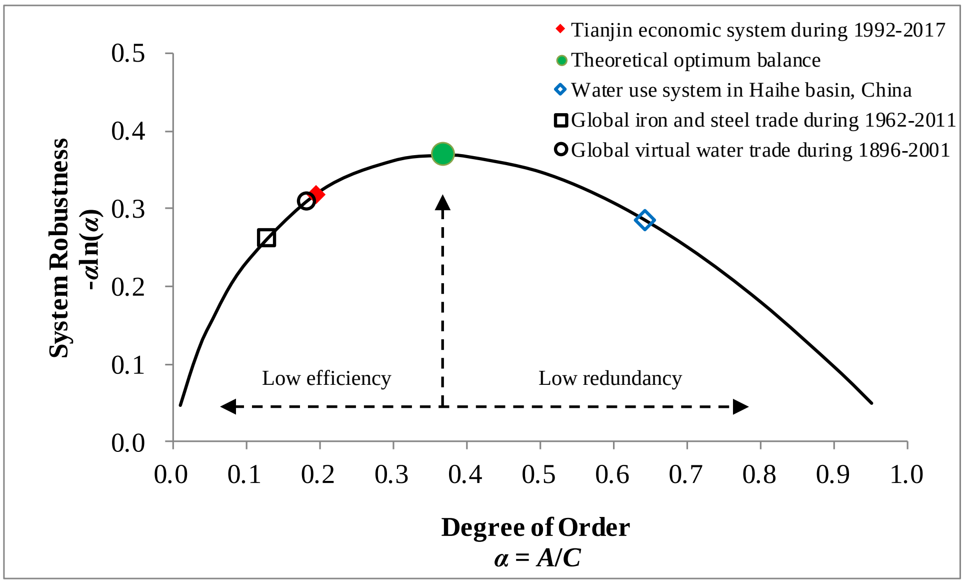
Table 2: The contribution of TST and AMI to ascendency (A) in the six-sector network of the Tianjin economy

Time interval	1992-1997	1997-2002	2002-2007	2007-2012	2012-2017	**Total of 1992-2017**
TST’s contribution	37%	79%	107%	74%	37%	**59%**
AMI’s contribution	63%	21%	-7%	26%	63%	**41%**

3.4. Sustainability analysis

The sustainability of a system can be estimated by analyzing the *A/R* ratio by using the ENA framework. However, this ratio is located in the range [0, +∞), which is not convenient for analysis or discussion. Thus, for convenience, we use $\alpha = (A/C)$, where $0 \le \alpha \le 1$, rather than the *A/R* ratio in our analyses. **Fig 5** shows that *α* for Tianjin City’s economic network presents an obvious rise from 1992 to 1997, but a small fluctuation during 1997-2017. The average value of *α* during 1992-2017 is 0.195.

According to Ulanowicz *et al.* (2009)[14], the system can maintain an optimal level of sustainability when $\alpha = (A/C)$ is close to 0.4596. This conclusion resulted from the observations of natural ecological networks. However, the processes within economic networks, such as a human-influenced network, are more complicated than those in natural ecological networks. For example, the currency flow can move bi-directionally between compartments (nodes) in an economic network, whereas in a natural ecological network, energy can only flow directly from, for example, a rabbit to a tiger, but not in the opposite direction[8]. Lietaer *et al*.(2009)[31] concluded that a human-influenced complicated network can maintain an optimal sustainable state when C is twice the value of A, which means the optimal value of α should be 0.33. Morris *et al*. (2005)[32] constructed thousands of random networks of various sizes and observed that a significant number of values of α clustered around 0.37, a value close to the asymptotic line of 1/e. In an empirical study, Kharrazi *et al*. (2013)[29] obtained an average value of α for the global virtual water trade network of 227 countries is 0.181 during 1896-2001; an average value of α for the global oil trade network of 137 countries is 0.199 during 2007-2011; an average value of α for the global steel trade network of 199 countries is 0.127 during 1962-2011.



Notes: The theoretical optimum value of α is 0.37 (Morris et al., 2005). The α values in the global iron and steel trade network and the global virtual water trade network are derived from (Kharrazi et al. 2013).

Figure 6: The average values of α in Tianjin City's economic network during 1992-2017, and a comparison between the theoretical optimum value of α and empirical values of α in several human-influenced networks.

In Tianjin City's economic network, the average value of α is 0.195 for the period 1992–2017, which is far less than the theoretical sustainability optimal value of 0.37 for human-influenced networks. It is also less than the empirical values of α for the global iron and steel trade network and the global virtual water trade network (**Fig 6**). From the ENA perspective, a system in this condition is weakly constricted by structure and lacks organizational efficiency. The system needs to improve its efficiency to maintain a sustainable level of evolvement. If an economy, as a human-influenced network, is comparable to this theoretical optimal magnitude, it would appear that Tianjin City's economic system needs to improve its efficiency to maintain its sustainable evolvement.

4. Conclusion

This study presents the construction of a six-sector economic network model for Tianjin City, with the network indicators for growth, development, and sustainability assessed utilizing the ENA methodology. The economic efficiency and resilience characteristics of Tianjin City from 1992 to 2017 have been comprehensively examined through an analysis of these network indicators.

The trend analysis of the network indicators reveals an exponential increase in the total system throughput (*TST*) of Tianjin City's economic system from 1992 to 2017, signifying rapid growth in the economic system's scale. This observation is consistent with the general trend observed in developing countries, where an increase in GNP is typically associated with a rise in *TST*. However, the trend in the *AMI* exhibits a two-phase pattern. Between 1992 and 1997, there is a pronounced change in both *AMI* and *H*, with the rate of increase in *AMI* exceeding that of *H*, suggesting an improvement in economic efficiency coupled with a decline in resilience. From 1997 to 2017, both *AMI* and *H* remained relatively stable, indicating no significant changes in efficiency and resilience.

Although the AMI values for the period between 1997 and 2017 are markedly higher than those in 1992, indicating a certain degree of increased network efficiency and economic development in Tianjin City, the magnitude of this increase is less pronounced than that of *TST*. The predominant feature of Tianjin's economy during 1992-1997 is thus characterized by size growth.

Quantitative analysis of the network confirms that *TST* accounts for approximately 59% of the ascendancy (A) of the network over the study period, while *AMI* contributes only 41%. This delineates that the growth in network size and the development in network efficiency have respective contributions of 59% and 41% to the Tianjin economy from 1992 to 2017.

The calculated average value of the sustainability indicator (α) for Tianjin City's economic network for the entire period is 0.195, significantly below the theoretical optimal value for sustainability of 0.37. Should the theoretical value of 0.37 be deemed an appropriate benchmark for an economic system's sustainability, it suggests that Tianjin City's economic system requires enhancement in efficiency to ensure its sustainable evolution.

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