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ENTROPIC ANALYSIS: UNDERSTANDING ECONOMIC SECTOR RELATIONSHIPS WITH LEONTIEF'S INPUT-OUTPUT TABLES

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Abstract. The article delves into the evolution of the "entropy" concept and its corresponding theoretical interpretations. Employing Shannon's entropy formula and leveraging the methodology of entropy calculation through Leontief's input-output tables, the study conducts entropy calculations for the economic systems of Australia, the Republic of South Africa, the United States, Luxembourg, Russia, South Korea, Japan, India, and China. These calculations are based on the tables published by the Organization for Economic Cooperation and Development. The primary finding of the study can be summarized as follows: Economic entropy, determined through the coefficients of total costs in Leontief's input-output tables, serves as a gauge of the interconnectedness among various branches within the economic system. Furthermore, financial and economic crises, as well as natural disasters, contribute to an escalation in the interconnectedness of economic branches, signifying a rise in entropy.

Key words - entropy, input-output tables, uncertainty, economic complexity, economic volatility, information theory, multi-theorization of the economy

Introduction

The concept of entropy in the natural sciences quantifies the level of disorder within a system composed of numerous elements. Specifically, in statistical physics, entropy signifies the likelihood of a macroscopic state's occurrence; in information theory, it denotes the degree of uncertainty surrounding an experiment with multiple potential outcomes; and in computer science, it measures the incompleteness and uncertainty inherent in information.

In economic theory, entropy serves as a metric for gauging the level of uncertainty within an economic framework. Its application in economics has expanded significantly, giving rise to novel scientific disciplines such as econophysics, complexity economics, and quantum economics. These fields introduce innovative methodologies; for instance,

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econophysics challenges the efficient market hypothesis, while complexity economics suggests that markets and economies operate optimally at the brink of chaos. Jakimowicz (Jakimowicz A., 2020, pp. 1-25) finds that incorporating entropy into econometrics has enriched the analytical toolkit, with non-extensive cross-entropy econometrics emerging as a valuable addition. This approach complements traditional econometrics by enabling the estimation of models for non-ergodic inverse problems, accounting for anomalies and misbehavior within economic systems.

The primary objective of this study is to investigate the impact of the global economic crisis of 2008-2009 on the entropy levels of the economic systems in various countries.

Our hypothesis posits that the computed entropy value mirrors the extent of interconnectedness among different sectors of the economy, rather than indicating the level of economic complexity.

Theoretical foundations of entropy

The concept of entropy was initially introduced by the German physicist Rudolf Clausius in 1865. Clausius (Clausius R., 1934, pp. 130-159) revolutionized the understanding of thermodynamics by substituting the word "transformation" with the ancient Greek term "entropy," thereby offering a fresh formulation of the Second Law of Thermodynamics: "Entropy remains constant in a closed reversible process." Expanding upon this principle to encompass natural changes, Clausius proposed that "the entropy of the universe tends towards maximum," consequently hypothesizing the eventual "heat death of the universe." Ludwig Boltzmann furthered the application of entropy in thermodynamics by linking it to probability theory. According to Boltzmann, the entropy of a system in certain states is proportionate to the logarithm of the probability of that state. In 1900, Max Planck formalized Boltzmann's concept of entropy, providing it with a definitive mathematical expression.

$$S = k ln(\Omega) \quad (1)$$

where S is the entropy, k is a constant, and Ω is the thermodynamic probability.

In 1929, Leo Szilard's article titled "On the Reduction of Entropy by the Intervention of a Thinking Being in a Thermodynamic System" was published. In this seminal work, Szilard proposed that a system comprising a small number of molecules could experience an increase in its level of organization through the intervention of a thinking being, who provides information. This concept highlighted a fundamental distinction between information entropy and thermodynamic entropy (Davtyan G., 1981, pp. 138-145).

The concept of entropy undergoes further development in cybernetics and information theory, where it becomes intricately linked to the notion of information. In this context, any information is acquired through the minimization of entropy. Information entropy serves as a metric for quantifying the level of uncertainty regarding the state of a system. Consequently, there arises a need to measure entropy. Claude Shannon addresses this need by proposing the following formula for measuring the entropy, denoted as H(a), of a physical system:

$$H(a) = -\sum_{i=1}^{k} p(A_i) \, log \, p(A_i) \quad (2)$$

where A_1, $A_{2,}$... A_k are the possible states of the physical system or the possible outcomes of any experiment, and , $p(A_1)$, $p(A_2)$..., $p(A_k)$ are the probabilities of being in those states or the outcomes occurring.

In the realm of contemporary information technologies, it is fitting to use a base-2 logarithm, as binary digits (0 or 1) can be stored in the memory cell of a calculator operating on a binary principle with equal probability (Nalchajyan T. & Nalchajyan V., 2017, p. 10). According to Shannon's formula, the entropy of the system would be calculated as (Shannon C., 1966, p. 245):

$$H(a) = -\left(\frac{1}{2} log_a \frac{1}{2} + \frac{1}{2} log_a \frac{1}{2}\right) = log_a 2 \quad (3)$$

When using a base-2 logarithm, the uncertainty level corresponds to 1. In this context, uncertainty is quantified in bits. Specifically, 1 bit represents the uncertainty of a system that can exist in either of two distinct states with equal probability.

Nicholas Georgescu-Roegen's (Georgescu-Roegen N., 1971) work "The Entropy Law and the Economic Process" provided a rationale for the utilization of entropy in economics. The author posited that all natural resources utilized in economic endeavors undergo irreversible degradation, resulting in a decline in the Earth's capacity to satisfy human needs. This phenomenon, according to Georgescu-Roegen, will inevitably culminate in humanity's extinction. Due to the physical degree of entropy (decreasing system order and increasing uncertainty), such an approach was called "entropy pessimism". Previously, Kenneth Boulding (Boulding K., 1966, pp. 3-14) proposed examining the relationship between the economy and the environment through the lens of thermodynamic laws. According to the second law of thermodynamics, also known as the law of entropy, achieving 100 percent secondary recycling of waste is unattainable. A portion of waste inevitably accumulates because it cannot be transformed into new resources. Consequently, Boulding emphasized the importance of directing all efforts towards minimizing waste generation and maximizing its secondary processing. In alignment with this line of reasoning, Herman Daly (Daly H., 1991, pp. 180-194) advocates for the concept of a steady or static economy, which stands in contrast to the notion of perpetual growth. Daly argues that in a steady-state economy, the output of energy and resources is harmonized with the environment's capacity to absorb waste and replenish resources. Conversely, an economy predicated on ceaseless expansion will inevitably deplete resources and degrade the environment, driven by the escalation of entropy stemming from production processes.

Sieniutycz and Salamon's (Sieniutycz S. & Salamon P., 1990) work, "Finite Time Thermodynamics and Thermoeconomics," delves into thermoeconomics as an alternative economic doctrine that integrates the principles of statistical mechanics into economics. Additionally, in 2021, Barclay Rosser (Rosser B., 2021, pp. 1-15) examined the correlation between econophysics and the law of entropy as the fundamental underpinning of economic phenomena. The paper elucidates how the interplay between entropy and anti-entropy can influence various aspects, such as the dynamics of business cycles, financial markets, and income distribution.

Skolka (Skolka V., 1964) and Theil (Theil H. & Pedro U., 1967, pp. 451-462) explored the application of entropy measures in Leontief's input-output tables in their works. Specifically, Theil examines entropy as a metric for capturing the uncertainty or information content inherent in economic data. Additionally, Batten's (Batten D., 1981) research demonstrates the utilization of the maximization of entropy paradigm, in its conventional form, within the realm of spatial and extraspatial analysis of costs and outcomes. When discussing input-output spatial analysis, special attention is paid to orthogonal and dynamic extensions of Leontief's original model, proposing a simple aggregation scheme based on the minimum information loss criterion. Given the limitations of static formulations in depicting aggregate interregional flows between sectors, Leontief's dynamic model proves instrumental in addressing this challenge.

Zwick and Heiat (Zwick M. & Heiat A., 1982, pp. 266-268) proposed applying Shannon's entropy index to various components of technical coefficient matrices, interdependence coefficients, the final demand vector, and other facets of cost-output tables. These entropy indices function as metrics for assessing different forms of economic diversity. The significance of these indicators for economic planning and analyzing the structural complexity of the economy and its evolution is emphasized.

Zachariah and Cockshott (Zachariah D. & Cockshott P., 2017, pp. 1-9) introduced a methodology for quantifying the complexity of multi-sector economies of countries, drawing on Shannon's entropy concept. Adopting V. Leontev's perspective, which defines the production process as a circular flow, they examined the national economies of seven countries and formulated the process using a Markov chain approach. The complexity of the economy, as derived from their research, is characterized by the average number of bits required to encode the flow of goods and services within the production process. The article faces several fundamental limitations: 1) Calculations for individual countries are conducted based on data from different years, leading to potential inconsistencies. 2) The branch structure of the national economies across countries does not align, which may impede meaningful comparisons. 3) Quantitative comparability is compromised as the branches within the national economies of the countries are not standardized.

We contend that comparing the complexity of different economic systems solely through an assessment of economic system complexity is inherently flawed without aligning the sectoral structures of the countries involved. Meaningful insights into the similarities or differences between these economies cannot be gleaned otherwise. Every qualitative change in systems manifests quantitatively, but for this quantitative measure to accurately reflect the qualitative changes in systems and facilitate comparative analysis, it's imperative that certain states of systems are measured using consistent methodologies. Accurate comparison of two phenomena necessitates an appropriate common basis of comparison, which is lacking in this case. The discrepancies in methodology highlighted by the authors underscore the inherent limitations of the paper.

In contemporary times, economic complexity serves as a gauge of a country's development and diversification of production capacity, typically assessed through the composition of its export basket. We argue that calculating entropy using Leontief's input-output tables is inadequate for characterizing economic complexity. This is because Leontief's tables represent circular processes, and entropy calculated using Shannon's formula does not inherently reflect the level of development, scientific advancement, or diversification within the system. Even without formal calculation, it's evident that economic complexity entails more than just the variety of branches. It's worth noting that the definition of economic complexity, as described, has been circulating in scientific discourse since 2009. However, contemporary assessments of economic complexity often employ different methodologies, such as the Economic Complexity Index.

When entropy is calculated using a logarithm base of 2, increasing entropy by 1 unit is equivalent to doubling it. Consequently, even a small deviation in entropy can lead to a significant disparity between economies of different countries. However, the authors, while analyzing data for the 1990s of various countries, fail to ensure the quantitative relevance of clear temporal and sectoral structures. Despite this, they note that the entropy levels in the 1990s are comparable among developed industrial countries.

Based on the considerations outlined above, our calculations ensure the comparability and consistency of data. We utilized data from the same time period and included identical economic sectors in the analysis for all countries. The data was sourced from the Organization for Economic Co-operation and Development (OECD), which offers uniform information across represented countries. In essence, the calculations for all countries were conducted using the same methodology, ensuring a standardized approach to the analysis.

Research methodology

To comprehensively depict the relationships among the branches constituting the economic system, the final production within each branch is preceded by the flows of goods and services exchanged between that branch and others. In 1936, the American economist Wassily Leontief pioneered the compilation of input-output tables, also known as inter-branch balance tables. To illustrate the composition and structure of these tables, let's employ the following designations:

- x_i, gross output of i-th industry
- y_i, *t*he volume of output released in the i-th branch, which is intended for final consumption in the non-production sector
- x_{ij}, the volume of output of the i-th branch that is consumed during production in the j-th branch

Table 1

Input-output table for an economy consisting of n industries branch (Leontief W., 1986, p. 168)

	INTERSECTORAL FLOWS							Final consumption	Total Products
	branch 1	branch 2	...	branch j	…	branch n			
branch *1*	x_{11}	x_{12}	…	x_{1j}	…	x_{1n}		y_1	x_1
branch *2*	x_{21}	x_{22}	…	x_{2j}	…	x_{2n}		y_2	x_2
…	…	…	…	…	…	…		…	…
branch *i*	x_{i1}	x_{i2}	…	x_{ij}	…	x_{in}		y_i	x_i
...	…	…	…	…	…	…		…	…
branch *n*	x_{n1}	x_{n2}	…	x_{nj}	…	x_{nn}		y_n	x_n

Initial investment	z_1	z_2	...	z_j	...	z_n	
Total. investment	x_1	x_2	...	x_j	...	x_n	

The rows of the table display the gross output of each industry and how that output is utilized by all industries. Conversely, the columns represent the investments made by all branches into the output of the specified branch. The balanced nature of the table is characterized by the following condition being applicable to any branch:

$$x_i = x_{i1} + x_{i2} + ... + x_{in} + y_i \quad (4)$$

Currently, such tables are compiled for 71 branches of the economy in the US every year (Input-Output Accounts Data, 2024).

There are 2 main methods of calculating entropy in the input-output table.

1. Calculation of entropy using direct cost coefficients,
2. Calculation of entropy using full cost coefficients (Zwick M. & Heiat A., 1982, pp. 266-268).

Denote $a_{ij} = \frac{x_{ij}}{x_j}$. This ratio denotes the cost incurred by the i-th branch to produce one unit of currency or one unit of output in the j-th branch, or the quantity of output from the i-th branch in the j-th branch. These ratios are referred to as direct cost ratios.

We can express the Leontief model in matrix form as follows:

$$X = AX + Y \quad (5)$$
$$(I - A)X = Y \quad (6)$$
$$X = (I - A)^{-1}Y \quad (7)$$

X represents the vector of gross output, Y signifies the vector of final consumption, A stands for the matrix of direct cost coefficients, and I denotes the unit matrix of order n. Let's denote: D=$(I - A)^{-1}$: Let's denote the elements of matrix D as d_{ij}, which indicate how much the volume of gross product in the i-th branch should increase if the final consumption of the j-th product is increased by one unit[1]. These d_{ij}'s are referred to as full cost ratios. After normalizing all rows of matrix D such that the sum of elements in each row equals 1, we obtain a new matrix, B_H. Using this matrix, we can calculate the entropy of each sector using the following formula:

$$H_j = -\sum_{i=1}^{n} b_{ij} \log_2 b_{ij}, \quad (8)$$

where

$$b_{ij} = \frac{d_{ij}}{\sum d_{ij}}$$

[1] As a result of the derivation of the equation $x_i = d_{i1}y_1 + \ldots + d_{ij}y_j + \ldots + d_{in}y_n$ by y_j, we get d_{ij}.

One can also compute a higher-order entropy for the entire economy:

$$H = -\sum_{j=1}^{n} H_j \, log_2 \, H_j \text{ , (9)}$$

where H_j is to be normalized. The magnitude of H_j increases when there are fewer non-zero elements in each row of matrix B and these elements are similar in size. Here's what it means: If there are no zero elements in the B_H matrix, it indicates complete interconnectedness among all branches of the economy, due to the significance of b_{ij} elements. If $b_{ij} \neq 0$, an augmentation in the final consumption of the j-th branch is contingent upon an increase in the gross output of the i-th branch. If these elements are closely matched in magnitude, the interdependencies among branches are equally evident, resulting in a higher entropy for the entire economy as a measure of their interconnectedness.

Entropy calculation for analyzing the diversity of product and service flows can be done using direct cost ratios. Both input and output entropy can be defined for each branch:

$$H_j^{input} = -\sum_{k=1}^{n} a_{kj} \, log_2 \, a_{kj} \text{ (10)}$$

$$H_j^{output} = -\sum_{k=1}^{n} a_{jk} \, log_2 \, a_{jk} \text{ (11)}$$

A sector with high output entropy contributes more diversely to the economy compared to a sector with low entropy.

Results

In our research, we analyzed the entropy of the economies of nine randomly selected countries from 2005 to 2015. This period was chosen to examine the impact of the global economic crisis of 2008-2009 on the entropy of these countries' economies.

Leontief's input-output table, which provides insights into the economies of the countries, consisted of 36 branches for all countries during the considered period (Input-Output Tables (IOTs), 2021 ed.), serving as the foundation for comparisons. Our objective was to determine whether entropy accurately reflects the economic reality and to evaluate how the interdependence among economic branches changes due to asymmetric processes within each country's economy.

We utilized the matrix of total cost ratios as the foundation for calculating entropy. This choice was driven by the fact that changes in the relationships between branches, stemming from ongoing developments in information and communication technologies within both the real and financial sectors of the economy, are captured in the matrix of total cost ratios. The findings of our study are detailed in Table 2.

Table 2

Economic entropy of countries in 2005-2015 (*Source:* Developed by the authors)

Year	India	China	Australia	South Africa	USA
2005	5.096672905	5.117259564	5.114269934	5.111861524	5.107095605
2006	5.09876344	5.117632133	5.1116781	5.110095537	5.105424932
2007	5.098191907	5.113310265	5.108362625	5.108194685	5.101727284
2008	5.099447733	5.113945703	5.112247239	5.108377411	5.099238008
2009	5.103907792	5.112651814	5.113214141	5.116832058	5.088330952
2010	5.097108133	5.10745469	5.112136847	5.112780889	5.114982399
2011	5.099021941	5.10928829	5.112667518	5.109908654	5.114957025
2012	5.098264819	5.108389538	5.117064203	5.108094638	5.09184516
2013	5.096259683	5.106886532	5.113739748	5.108214749	5.092043901
2014	5.094948008	5.105986893	5.113610687	5.108162581	5.093672294
2015	5.104494145	5.109304762	5.118046809	5.108450847	5.09132977

Table 2

Economic entropy of countries in 2005-2015 (cont.)

Year	Luxembourg	Russian Federation	South Korea	Japan
2005	5.067647919	5.106793367	5.11441856	5.10909184
2006	5.067012283	5.110269971	5.116082744	5.110150847
2007	5.072221737	5.109246567	5.116123294	5.110762337
2008	5.076759953	5.110247014	5.116774785	5.112366142
2009	5.077335451	5.1108088	5.119501355	5.110306551
2010	5.084195319	5.111368893	5.118263671	5.111316816
2011	5.083890635	5.113657117	5.118607523	5.111986745
2012	5.088572472	5.111947614	5.118768269	5.110842386
2013	5.092401349	5.112528076	5.119729876	5.11142607
2014	5.093769933	5.113573232	5.116183386	5.112336164
2015	5.096358542	5.121909724	5.114065112	5.111402637

Figure 1

Economic entropy of countries in 2005-2015 (*Source:* Developed by the authors)

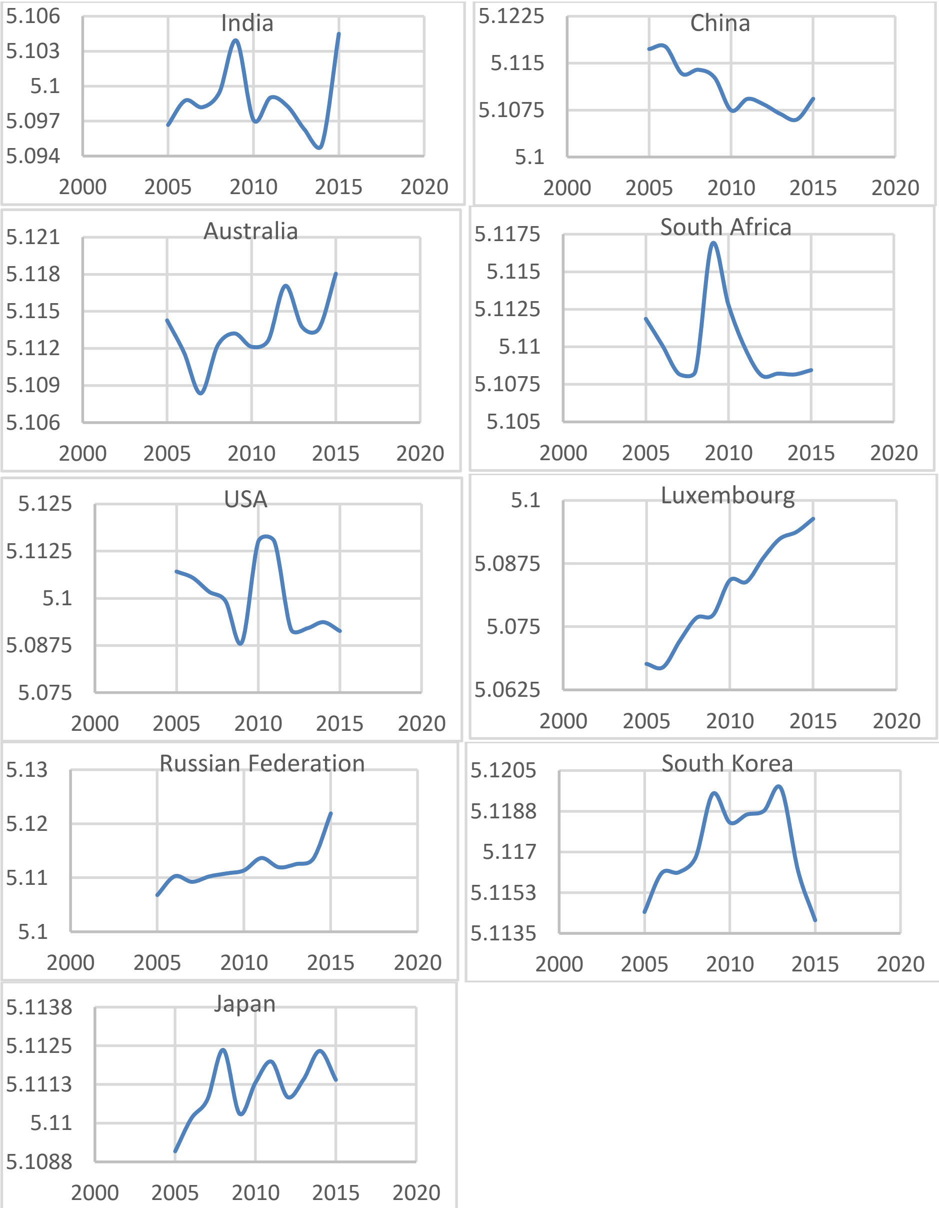
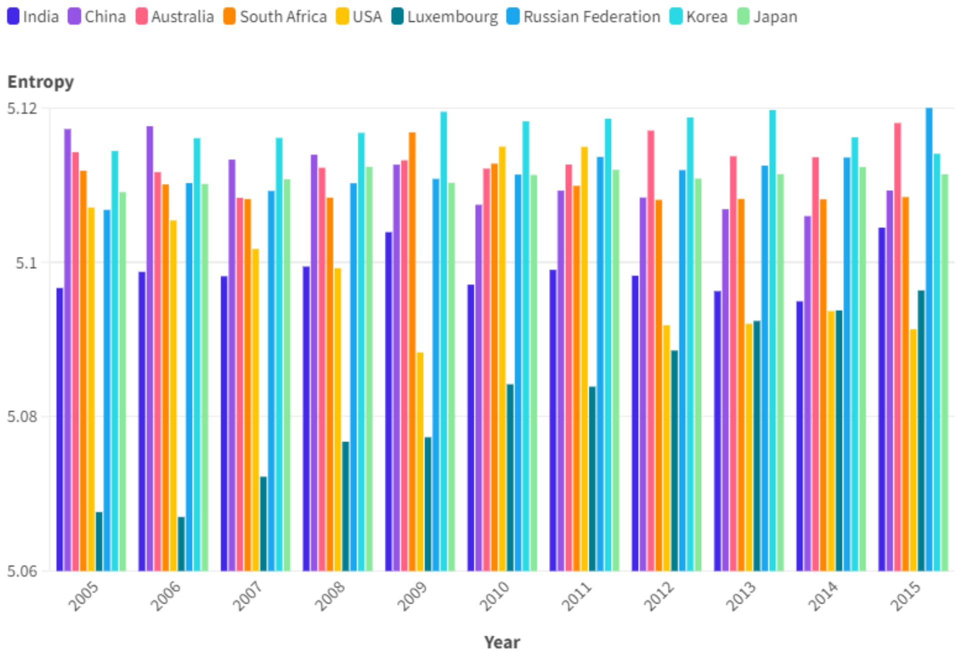


Figure 2

Economic entropy of countries (*Source:* Developed by the authors)



The period under consideration encompasses the global financial and economic crisis of 2008, which left its mark on the entropy of countries. In specific instances, entropy exhibited significant fluctuations, influenced by economic, political, social, and other factors within each country.

A high entropy value indicates a complex and diversified economic structure, necessitating a broad array of inputs from various sectors to meet final demand. Conversely, a lower entropy value signifies a more centralized economic structure, with fewer sectors contributing to final demand satisfaction. This indicates a heightened level of interdependence among economic sectors.

As depicted in the graphs, entropy experienced a notable increase across all countries in either 2008 or 2009, attributed to a sharp global demand downturn, disruptions in trade finance, and a general economic downturn impacting both exports and imports. Consequently, the level of interdependence among industries within the economy inevitably rose, as local production replaced imports.

The United States, being the epicenter of the crisis, witnessed significant shifts in its trade balance due to diminished exports and imports, stemming from sharp declines in consumer spending and industrial production. However, the level of interdependence among economic sectors peaked in 2011.

In Australia, entropy surged to a peak value in 2012, exhibiting an upward trajectory until that point. As the EU is one of Australia's largest trading partners, the European debt crisis contributed to this trend by inducing heightened uncertainty, increased volatility, and alterations in trade patterns. These factors collectively bolstered the interdependence among domestic sectors. Additionally, natural disasters such as floods and forest fires in 2012 further exacerbated the increase in entropy.

Meanwhile, entropy in Russia peaked in 2015. During this period, Russia encountered substantial economic challenges, including a sharp decline in oil prices, resulting in deteriorating terms of trade. Given Russia's heavy reliance on the export of natural resources, this downturn had a significant impact. Moreover, geopolitical tensions starting in 2014 prompted economic sanctions, particularly those imposed by the European Union, which restricted investments in various sectors such as infrastructure, transportation, telecommunications, energy, as well as oil, gas, and mineral extraction.

When analyzing the evolution of Luxembourg's economic structure, a notable trend emerges. In the early 2000s, the economy exhibited a higher level of concentration, with a few dominant sectors such as industry and financial services. However, from 2004 onward, the government initiated efforts to diversify the economy across five main areas: information and communication technology, logistics, space industry, biotechnology, and eco-technology.

Significant investments in technology ensued, leading to the establishment of a robust technological infrastructure. Consequently, Luxembourg emerged as a frontrunner in the realm of digital technology. This transformative shift is vividly depicted in the entropy graph of the country, illustrating a steady increase in the interconnectedness of its economic sectors year after year.

In Japan, entropy peaked in 2011 and 2014. In 2011, a devastating 9.0 magnitude earthquake and subsequent tsunami struck off the east coast, resulting in the destruction of a nuclear power plant in Fukushima Prefecture. These catastrophic events necessitated a coordinated response from various economic sectors to facilitate the country's recovery.

As a consequence, the level of interdependence among economic branches surged, as concerted efforts were required across sectors to address the aftermath of the disaster and restore economic stability.

Conclusions

- Entropy, as an economic metric derived from the coefficients of total costs in Leontief's input-output tables, signifies the degree of interconnectedness among different branches of the economy. It's important to note that entropy does not encapsulate the complexity of the economy, which involves the computation of multi-dimensional characteristics of economic systems. Our hypothesis is confirmed.
- Natural disasters and financial crises in countries typically result in heightened interconnections between economic branches rather than weakening them. This phenomenon often translates into elevated entropy values, indicating increased interconnectedness within the economic system.
- Countries with economies concentrated in specific branches or specialized in particular areas tend to exhibit lower entropy values. Conversely, countries boasting diversified and complex economies typically display higher entropy values, reflecting the heightened interconnectedness among various sectors.

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