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ENTROPY BASED EVALUATION OF THE IMPACT OF EDUCATION ON ECONOMIC DEVELOPMENT

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Abstract. *In contemporary economic landscapes, effective managerial decision-making requires serious justifications often facilitated by information technologies. The article proposes the application of the foundational principles from information theory and entropy to determine the correlation between education and economic development. This research employs entropy methodology to explore the correlations and implications of these multifaceted domains, drawing insights from a range of global indices. By analyzing data from indices such as the Human Development Index, we investigate the relationship between average years of education and entropy values, shedding light on the diversity and standardization of human capital systems across nations. Moreover, economic indexes, encapsulating factors such as economic freedom and innovation, provide critical insights into the vibrancy and resilience of national economies. Through the lens of the Global Innovation Index, we explore how countries with higher levels of economic freedom and innovation efficiency exhibit less diversity in economic approaches and innovation strategies, leading to a reduction in entropy values. By examining entropy values in conjunction with innovation indicators, such as research and development expenditure and patent applications, we uncover patterns and trends indicative of the diversity or standardization of innovation strategies across countries. Additionally, cybersecurity emerges as a critical dimension of national security and resilience, with implications for economic well-being and societal trust. Through the National Cybersecurity Index, we assess the level of diversity and uncertainty in cybersecurity landscapes, highlighting the importance of robust cybersecurity measures in safeguarding against emerging threats and reducing entropy values. Ultimately, this research contributes to the discourse on sustainable development and resilience in an interconnected world. By identifying specific challenges and opportunities within education, economy, innovation, and cybersecurity domains, it facilitates informed decision-making and strategic interventions to promote inclusive growth and societal well-being on a global scale.*

Keywords: entropybased correlation, education development, economic indexes, innovation dynamics

ENTROPIJNA OCENA WPŁYWU EDUKACJI NA ROZWÓJ GOSPODARCZY

Streszczenie. *We współczesnym krajobrazie gospodarczym skuteczne podejmowanie decyzji menedżerskich wymaga poważnych uzasadnień, często ułatwianych przez technologie informacyjne. W artykule zaproponowano zastosowanie podstawowych zasad teorii informacji i entropii w celu określenia korelacji między edukacją a rozwojem gospodarczym. Badanie to wykorzystuje metodologię entropii do zbadania korelacji i implikacji tych wieloaspektowych dziedzin, czerpiąc spostrzeżenia z szeregu globalnych wskaźników. Analizując dane z indeksów takich jak Human Development Index, przebadano związek między średnimi latami edukacji a wartościami entropii, rzucając światło na różnorodność i standaryzację systemów kapitału ludzkiego w różnych krajach. Co więcej, indeksy ekonomiczne, obejmujące takie czynniki jak wolność gospodarcza i innowacyjność, zapewniają krytyczny wgląd w żywotność i odporność gospodarek krajowych. Przez pryzmat Globalnego Indeksu Innowacji zbadano, w jaki sposób kraje o wyższym poziomie wolności gospodarczej i wydajności innowacji wykazują mniejszą różnorodność w podejściach gospodarczych i strategiach innowacyjnych, co prowadzi do zmniejszenia wartości entropii. Badając wartości entropii w połączeniu ze wskaźnikami innowacyjności, takimi jak wydatki na badania i rozwój oraz zgłoszenia patentowe, ustalono wzorce i trendy wskazujące na różnorodność lub standaryzację strategii innowacyjnych w różnych krajach. Ponadto cyberbezpieczeństwo staje się krytycznym wymiarem bezpieczeństwa narodowego i odporności, co ma wpływ na dobrobyt gospodarczy i zaufanie społeczne. Poprzez Krajowy Indeks Cyberbezpieczeństwa oceniono poziom różnorodności i niepewności w krajobrazach cyberbezpieczeństwa, podkreślając znaczenie solidnych środków cyberbezpieczeństwa w ochronie przed pojawiającymi się zagrożeniami i zmniejszaniu wartości entropii. Ostatecznie badania te przyczyniają się do dyskursu na temat zrównoważonego rozwoju i odporności w połączonym świecie. Identyfikując konkretne wyzwania i możliwości w dziedzinie edukacji, gospodarki, innowacji i cyberbezpieczeństwa, ułatwione jest podejmowanie świadomych decyzji i strategicznych interwencji w celu promowania wzrostu sprzyjającego włączeniu społecznemu i dobrobytowi społecznemu w skali globalnej.*

Słowa kluczowe: korelacja entropijna, rozwój edukacji, wskaźniki ekonomiczne, dynamika innowacji

Introduction

In the dynamic landscape of global socio-economic development, understanding the intricate interplay between various factors is essential for devising effective strategies to foster growth and stability. Among these factors, education development, economic indexes, innovation, and cybersecurity play pivotal roles in shaping the trajectory of nations.

This research endeavors to explore the correlation between education development and economic indexes within the framework of entropy methodology. By integrating insights from multiple indices, including the Global Innovation Index, the Human Capital Development Index, and the Cybersecurity Rating, this study aims to elucidate the complex dynamics influencing societal progress.

Education stands as a cornerstone of societal advancement, serving as a catalyst for economic growth, social stability, and technological innovation. Moreover, innovation plays a transformative role in driving economic prosperity and competitiveness on a global scale. The ability to foster innovation and harness human capital effectively is indicative of a nation's capacity to navigate the challenges of the digital age.

In this context, cybersecurity emerges as a critical dimension of national security and resilience, with implications for economic well-being and societal trust. The increasing interconnectedness of digital infrastructure underscores the importance of robust cybersecurity measures in safeguarding against emerging threats.

By applying entropy methodology, this research seeks to provide a nuanced understanding of the correlation between education development, economic indexes, innovation, and cybersecurity. Through empirical analysis and statistical modelling, we aim to uncover underlying patterns and trends that shape the complex interactions between these domains.

The objective of this research is to enhance the application of entropy estimation methods for the comprehensive evaluation of complex socio-economic systems. The primary contributions of this work include:

1. The development of an information technology framework that leverages entropy-based socio-economic indicators to elucidate the relationship between education and economic development.
2. A detailed investigation of the correlation between education and economic development.
3. Through the analysis of data, such as the Human Development Index, a significant association was identified between the average number of years of education and entropy values.
4. By examining factors such as economic freedom and innovation, a nuanced understanding of the dynamics and sustainability of national economies was achieved.

The research is organized as follows. The "Literature Review" section outlines directions of previous and current scientific studies addressing the issues in the impact of education on the economic development. The "Materials and Methods" section details the initial data for the study and formally describes the methods used. In the "Experiments and Results" section, we present a structural model, along with the process of discretization and sensitivity analysis. The "Discussion" chapter analyzes the results and identifies trends that evaluate the impact of education on economic development. The "Conclusion" chapter summarizes the findings and suggests promising directions for future research. The "References" chapter provides a list of sources that form the foundation of the proposed research.

1. Literature review

The scientific research on the correlation between education development and economic indexes reveals a consensus among researchers regarding the strategic importance of education in the state's development and integration into the global community. Education serves multifaceted roles, including personnel training, fostering political and social stability, nurturing civil society institutions, and enhancing the security of both citizens and the state. However, the global economic crisis has underscored the vulnerability of education systems to economic downturns, as it affects all spheres of socio-economic life. A socio-economic system is an interconnected network of social and economic elements, including individuals, institutions, and markets, that work together to allocate resources and meet human needs. It is shaped by social norms, regulatory frameworks, and feedback mechanisms, which influence behaviors and economic activities. The system is dynamic, adaptable to change, and seeks to balance efficiency, equity, and sustainability.

Scholars such as O. Hrishnova [4], U. Husar [6], V. Lytvynenko [14], N. Savina [13], and others have extensively studied the challenges and opportunities in education development. They emphasize the need for education to adapt to the evolving demands of the knowledge economy and information society, particularly in the face of economic crises. Efforts to address the negative consequences of economic downturns often focus on sectors directly impacted by basic economic indicators, neglecting relatively autonomous spheres like education.

Research conducted by S. Kahkonen [7] for the World Bank has shed light on the unsustainability of Ukraine's education system, highlighting the need for comprehensive reforms. Moreover, scholars such as David E. Purpel, William M. McLaurin, Rachel Purpel [12], and G. Badley [1] have examined the impact of economic crises on education systems globally, emphasizing the need for innovative approaches to mitigate their effects.

In the context of the knowledge economy, where education is increasingly commercialized, scholars like Keller Katarina R.I. [8] have examined the implications of economic crises on education systems. They argue that education must evolve to meet the needs of the information society while navigating the challenges posed by economic instability.

Overall, the literature underscores the complex interplay between education development and economic indexes, highlighting the need for holistic approaches and innovative methodologies, such as entropy analysis, to unravel these dynamics effectively.

2. Materials and methods

In this study, we adopt a methodology grounded in the principles of information theory and entropy to assess the interplay between education system factors and economic outcomes. Given the complexity of these interactions and the need for real-time risk forecasting and management, it is essential to evaluate the significance of individual influences within the education system on its overall results.

Traditional methods of risk assessment often overlook the functional relationships among factors, necessitating a novel approach. By conceptualizing risk as information about the quantitative uncertainty surrounding the final state of economic outcomes, we justify the utilization of entropy-based risk assessment.

Entropy, initially introduced in thermodynamics to characterize the irreversible dissipation of energy, has found applications in diverse fields. In physics, it serves as a measure of the probability of various macroscopic states. In information theory, entropy quantifies the uncertainty associated with the outcomes of an experiment.

In our context, we view risk as the likelihood of undesirable outcomes within the education system and broader economic activity. Leveraging information theory allows us to assess risk comprehensively, accounting for the multifaceted uncertainties inherent in economic and educational dynamics.

Through this methodology, we aim to elucidate the functional relationships between education system factors and economic outcomes, providing insights into risk management strategies and enhancing our understanding of the complex interactions shaping societal development.

For a financial and socio-economic system characterized by uncertain states, we can apply the principles of static physics and information theory to estimate the system's entropy, which represents the uncertainty of its final outcome.

If a system can exist in n states, each described by the probabilities denoted as $X_1, X_2, ..., X_n$, where $P_1, P_2, ..., P_n$ are the probabilities of these states and sum up to 1 ($P_1 + P_2 + ... + P_n = 1$), then the probability of an event's state is fully determined.

In information theory, the probability of a state serves as a numerical measure of the likelihood of a random event occurring, typically expressed as fractions of a unit or percentages.

Thus, for a discrete probability distribution P_n, the entropy of the system is defined as:

$$H(a) = -\sum_{k=1}^{n} P_k \log_q P_k \quad (1)$$

where:

$q > 1$ – the basis of the system of logarithms.

Or

Thus, for a discrete probability distribution p_i, the entropy of the system is defined as [11]:

$$\hat{H} = -\sum_i p_i \ \log p_i \quad (2)$$

where:

p_i is probability of the i-event, assessment, estimated as the frequency of this event in the sample.

The relationship presented in equation (1) is fundamental in information theory, serving as the basis for defining a unit of information as a measure of event uncertainty. To quantitatively estimate the entropy of a system according to equation (1), the choice of the logarithm base is crucial.

In information theory, the base of the logarithm is typically chosen as 2, the smallest integer greater than one. This choice is justified by considering the uncertainty of the socio-economic system, which is influenced by information about market states or other system parameters. Therefore, using the number 2 as the base for determining the entropy of the socio-economic system is appropriate.

The expression in equation (1) represents the uncertainty of one possible state of the final event, with its value indicating the entropy of that state. It should be taken into account that in the equation (1), the uncertainty of the state of the system, denoted as $H(a)$, is reduced to zero when one of the possible states is reliable $P_k = 1$, that is, it reaches a maximum with equally probable events P_k.

$$P_k = \frac{1}{n} \quad (3)$$

where: P_k is the probability of the K^{th} state of the event; n is the number of possible equally probable states of the system.

The equation ($P_k \log_2 P_k$) in (1) should be considered as the uncertainty of one of the possible states of the final event, and its value with the opposite sign – as the entropy of the k^{th} state of this event.

In the context of socio-economic systems, probabilities of states (P_1, P_2, ..., P_n) in these expressions can be determined using statistical parameters such as root mean square deviations, variances, or other relevant statistical data.

Practical application of equation (1) in assessing the uncertainty of socio-economic systems involves calculating entropy values for various probabilities. Entropy, in this context, can be interpreted as a measure of the diversity or heterogeneity in economic phenomena. Decreasing entropy may signify a level of order or standardization in economic data, while increasing entropy may indicate greater diversity or heterogeneity.

The received probability P be interpreted as the degree of uncertainty. If $H(a)$ exceeds the maximum value achievable with $P = \frac{1}{n}$, the program will identify this as an error in the input data. When the number of possible states is unknown, we will assume they are equally likely, with $P_k = P = \frac{1}{n}, k = \overline{1,n}$. In this scenario, the discrete formula (1) will be applied regardless of the number of states n. As it was suggested in [11] to calculate the entropy of a discrete distribution, the formula provided:

$$H(a) = -\sum_{k=1}^{n} P_k \log_2 P_k = -n \cdot P \cdot \log_2 P = \log_2 P \quad (4)$$

Namely, generalizing this formula for uninterrupted even, we can count up the risk probability by the inverse formula $P = 2^{H(a)}$.

In order to minimize the time spent on calculating the probability of risk, a program for its calculation is proposed.

This paper incorporates the utilization of various estimators of Shannon entropy [3] through the implementation of a specialized package. Specifically, the package offers estimators that are applicable in scenarios characterized by "small n, large p" situations, where there are significantly more bins than counts.

The central function of this package is "entropy", which serves as a unified interface to access a diverse array of entropy estimators. Additionally, the package includes functionalities for estimating other information-theoretic measures such as Kullback-Leibler divergence (KL.plugin), mutual information (mi.plugin), and chi-squared divergence (chi2.plugin). Furthermore, auxiliary functions are provided to compute statistical measures like the G statistic (Gstat) and the chi-squared statistic (chi2stat) [3]. To calculate entropy, the entropy package of the R statistical data system was used (https://cran.r-project.org/web/packages/entropy). This package implements various entropy estimators, such as the Millow-Meadow estimator, various Bayesian estimators, and estimation.

The Miller-Madow method is used because it is a bias-correction method for estimating entropy in situations where the data sample is relatively small. This method addresses the bias that occurs when estimating entropy from finite samples.

When using a finite data sample to estimate entropy, bias arises because the sample may not accurately reflect the true probability distribution.

The Miller-Madow method corrects this bias by adjusting the standard entropy estimate.

To correct the bias in the Miller-Madow method, a correction term is added to the entropy estimate (2).

$$\hat{H} = \hat{H} + \frac{(k-1)}{2N} \quad (5)$$

where $\hat{H}$ is the entropy estimate based on frequencies, k is the number of different possible events (different outcomes), and N is the sample size.

In general, the Miller-Madow method enhances the accuracy of entropy estimation, particularly in situations with limited data, which makes it a valuable tool for addressing the challenges outlined in this work (*Alg.*).

By leveraging these tools, this research extends its analytical capabilities to encompass a comprehensive exploration of entropy dynamics within the domains of education development, economic indexes, innovation, and cybersecurity. This integration of specialized methodologies enhances the depth and breadth of the analysis, offering valuable insights into the complex interrelationships among these critical domains.

This formulation allows us to quantify the uncertainty within the socio-economic system based on the probabilities of its various states. By calculating the entropy, we gain insights into the system's overall unpredictability and can devise strategies to manage and mitigate risks associated with its uncertain outcomes.

Algorithm 1: Entropy Calculation Using the Miller-Madow Method

```
Initialization:
Set: vector y of values of observed process f
n = length(y)
# n -vector length
iteration counter i = 1
while i ≤ round(n − 1) do
  # Calculate entropy using Miller-Madow method
   entropy_MillerMadow(y)
  # Compare to empirical estimate entropy_empirical(y)
  # Increase counter for next iteration
  i = i + 1
end
# observed counts for each bin
y = [/ * Vector values for observed counts * /]
# Calculate entropy using maximum likelihood method entropy(y,
 method="ML")
```

3. Experiments and results

In this scientific study, we have identified three distinct groups of countries for analysis based on geographical proximity and level of development:

1. Group of Neighboring European Countries (similar population demographics)
   - Poland,
   - France,
   - Germany.
2. Group of Highly Developed Countries (representing diverse economic and socio-political contexts):
   - USA,
   - Great Britain (UK),
   - China.
3. Group of Middle Eastern Countries (reflecting the geopolitical and economic landscape of the Middle East region):
   - Turkey,
   - Israel,
   - Saudi Arabia.

These groupings allow for comparative analysis across different regions and developmental stages, providing insights into the correlation between education development and economic indexes within each group as well as potential contrasts and similarities between them. By examining countries with varying levels of development and diverse socio-economic contexts, we aim to capture the breadth of factors influencing the relationship between education and economic prosperity. Entropy based evaluation of the National Cybersecurity Index is provided in the table 1.

In analyzing the data from the National Cybersecurity Index [10], it becomes evident that countries vary in their levels of development in the field of cybersecurity education. For instance, Germany, Great Britain, and Saudi Arabia stand out with the highest indicators, each scoring 9 in this domain (Tab. 1). Despite their similar high scores, the entropy values for these countries differ slightly, indicating varying degrees of diversity or heterogeneity in their cybersecurity education approaches. On the other hand, Israel, with a lower score of 6 in cybersecurity education development, exhibits a higher entropy value. This suggests a greater diversity or heterogeneity in cybersecurity education compared to countries with higher national rankings.

Table 1. Entropy based evaluation of the National Cybersecurity Index

National Cybersecurity Index					
Country	Development of cyber security policy	State ability to identify threats	Development of cyber security education	Contribution to the global system of cybersecurity	Entropy
Ukraine	7	4	8	2	1.273647
Poland	7	5	7	2	1.298035
France	6	4	8	3	1.319422
Germany	7	5	9	3	1.313911
USA	7	1	8	6	1.227067
UK	5	5	9	6	1.354078
China	1	1	8	2	0.9830878
Turkey	6	1	4	3	1.239659
Israel	4	4	6	3	1.354581
Saudi Arabia	4	5	9	2	1.258048

Remarkably, China stands apart with the lowest entropy value despite having a high score of 8 in cybersecurity education development. This suggests a high level of coherence and standardization in China's cybersecurity education practices, possibly reflecting a consolidated approach and strategy in this critical domain.

The findings from the Global Innovation Index [2] reveal significant differences in the level of innovation and the effectiveness of scientific and creative results of innovative activity among countries, which in turn, greatly influence the entropy value.

For instance (Tab. 2.), Poland demonstrates notably high innovation and efficiency scores (41 and 36, respectively) compared to the United States (2 and 5) and China (21 and 8). This discrepancy may contribute to a higher degree of diversity and heterogeneity in innovative approaches and scientific and technical solutions within Poland. Consequently, this diversity can lead to an increase in entropy values, reflecting the wide array of innovative strategies and solutions employed.

In contrast, countries like the US and China, where innovation and performance rates are also high, may exhibit lower entropy values. This can be attributed to the likelihood of more consistent and standardized innovation strategies, resulting in less diversity of approaches and consequently, lower entropy values.

Therefore, the level of innovation and efficiency in scientific and technical activity emerges as a pivotal factor influencing the level of entropy within a country. It serves as a reflection of the degree of diversity and standardization in the realm of innovation, underscoring the complex interplay between innovation dynamics and entropy values on a global scale.

Table 2. Entropy based evaluation of the Global Innovation Index

Global Innovation Index			
Country	Innovation Input Sub-index	Innovation Output Sub-index	Entropy
Ukraine	75	48	0.6688571
Poland	41	36	0.6910374
France	13	11	0.6896709
Germany	12	7	0.65811
USA	2	5	0.5982696
UK	7	3	0.6108643
China	21	8	0.5890026
Turkey	49	33	0.6739882
Israel	22	16	0.6806295
Saudi Arabia	37	65	0.6549813

The analysis of the Human Development Index [5] reveals an interesting relationship between average years of education and entropy values across countries. Specifically, countries with the highest average years of education, such as Saudi Arabia, Poland, France, and China, exhibit the lowest entropy values (Tab. 3). This observation suggests that as the average years of education increase, there is a tendency towards less diversity or heterogeneity in the human capital system.

Table 3. Entropy based evaluation of the Human Development Index

Human Development Index				
Country	Life expectancy at birth	Expected years of schooling	Mean years of schooling	Entropy
Ukraine	71.6	15	11.1	0.7625745
Poland	76.5	16.3	11	0.7534912
France	82.5	15.8	11.6	0.7314573
Germany	80.60	17	14.1	0.7832358
USA	77.2	16.3	13.7	0.7857377
UK	80.7	17.3	13.4	0.7775237
China	78.2	14.2	7.6	0.6653217
Turkey	76	18.3	8.6	0.7383526
Israel	82.3	16.1	13.3	0.757627
Saudi Arabia	76.9	16.1	11.3	0.7539064

In countries characterized by high average years of education, a more standardized and coherent approach to education and human capital development is often observed. This standardization leads to a reduction in entropy values, indicating a more uniform distribution of educational attainment and skill levels among the population.

Therefore, the level of education plays a crucial role in shaping the diversity and heterogeneity of the human capital system within a country. Countries with higher average years of education tend to exhibit lower entropy values, reflecting a more homogenous and standardized approach to human capital development.

4. Discussion

Based on a comprehensive review of indices such as the Global Innovation Index [2], the Human Development Index [5], and the National Cybersecurity Index [10], several overarching conclusions can be drawn regarding their correlation with entropy values:

1. **Innovation and Entropy:** Nations with high rates of innovation and efficiency may display less diversity in their innovation strategies, resulting in a decrease in entropy values. This indicates a move towards a more standardized approach to innovation, which can be observed in highly innovative economies.
2. **Development of Human Capital and Entropy:** Countries with advanced human capital development, as indicated by a high number of average years of education, may demonstrate less diversity in their human capital systems. This contributes to a decrease in the significance of entropy, reflecting a more uniform distribution of educational attainment and skill levels among the population.

Overall, these general trends suggest that highly developed and economically free nations tend to exhibit less diversity and greater standardization in their approaches, leading to a reduction in significant entropy. In contrast, less developed or less economically free countries may display greater diversity, resulting in an increase in entropy values.

Considering specific indicators for Ukraine, the entropy values provide insights into various aspects of the economic, socio-technical, and cybersecurity spheres. Each indicator reflects not only the state of the economy but also the interaction of society with technological and social challenges. To address specific problems and develop effective strategies for reducing diversity and uncertainty, it is imperative to consider each individual indicator:

1. **Innovation and Entropy (0.6688571):** This entropy value highlights the level of diversity in innovation strategies in Ukraine. Supporting innovative infrastructure, fostering a favorable climate for startups, and increasing investment in research and development can contribute to reducing entropy.
2. **Human Development and Entropy (0.7625745):** This entropy value signifies a high level of human capital development in Ukraine. Programs aimed at continuous learning and professional skill development can help decrease entropy.

3. **Cybersecurity Index and Entropy (1.273647):** This entropy value indicates the diversity and uncertainty in Ukraine's cybersecurity landscape. Strengthening defense capabilities, implementing modern cyber defense technologies, and enhancing personnel skills are essential steps to mitigate cybersecurity risks and reduce entropy.

To effectively reduce entropy, strategies may include legislative reforms, education and research programs, innovation stimulation, and investment in critical areas. Additionally, ensuring transparent and effective governance and regulatory mechanisms is crucial for stability and development.

5. Conclusion

This research, based on information theory and entropy, provides a robust framework for examining the intricate relationship between education and economic development. Through rigorous analysis, it offers valuable insights into the dynamics of these domains, facilitating informed decision-making and strategic planning in modern economic contexts. Additionally, this methodology enables comparative analysis of strategies employed by different countries, thereby enriching our understanding of the diverse approaches to education and economic development on a global scale.

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Student for Ph.D. degree in Economics. Scienceswas born in Rivne, Ukraine and went to the Kyiv National Taras Shevchenko University, where he studied Korean language for bachelor degree and public administration for master degree. From 2021 he started his education for Ph.D. degree, analysing the impact of gambling regulation on a national economy.
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