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EVALUATION OF VIRTUAL AND PHYSICAL SOCIAL NETWORKS, OR THE IMPACT OF INTERNET USAGE AND URBANIZATION, ON COUNTRIES' GDP

Abstract: *In a hypercompetitive era, this paper assesses the impact of virtual and physical social networks on global economies. Thus, it assesses the correlation between the Gross Domestic Product (GDP) per capita and social networks represented by the physical concentration of humans in urban environments and the use of the Internet as a virtual space.*

This research examines the GDP per capita of 172 countries between 2000 and 2023. Through the use of Mean Absolute Percentual Error (MAPE) and the Weighted Least Squares (WLS), we propose a mathematical model that best fits the real GDP data.

The growth of the Internet has made it possible to reduce income inequality between countries. Furthermore, the mathematical model reveals that in 2020, the World radically shifted to the virtual space, and those who did not use the Internet faced major economic challenges.

Keywords: *social networks, virtual social networks, physical social networks, internet usage, impact.*

1. Introduction

Following Heraclitus' motto that nothing is permanent except change and "becoming" is the essence of reality, this paper examines the effects of changes in social networks in physical and virtual spaces, on wealth creation in countries. Thus, we ask how countries generate wealth by leveraging opportunities in digital (Internet) and physical (urban) networks.

The scientific discourse during the emergence of Industry 4.0 predominantly emphasized technocentric networks of things (Internet-of-Things - IoT, Cyber-Physical Systems - CPS, etc.), often overlooking the foundational role of human social behavior in economic systems. While technological interventions can shape economic interactions, they cannot fully replace the intrinsic sociocognitive and behavioral dimensions that strengthen organizational and market dynamics.

In recent years, however, human-centric approaches have regained prominence in management theory, particularly with the advent of so-called Industry 5.0 and Society 5.0. These paradigms recognize the necessity of integrating human agency alongside advanced technologies. Concurrently, advancements in artificial intelligence (AI) have enabled the deployment of virtual agents designed not to replace but to assist and expand human decision-making processes within organizational frameworks.

The evolution of production systems and their associated economic ecosystems has demonstrated that, beyond the physical networks that historically strengthened

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industrial revolutions, virtual networks (enabled by digital infrastructure) now offer transformative potential. These networks facilitate collaborative interactions between human agents and AI-driven virtual agents (e.g., autonomous AI systems, digital avatars), operating across real and virtual dimensions. This integration bridges the analog and digital worlds through technologies such as:

- Digital twins (virtual replicas of physical systems enabling real-time simulation and optimization),
- Metaverse platforms (persistent virtual environments blending human and AI interaction), and
- AI-augmented decision systems (where algorithmic agents assist in operational and strategic processes).

This paradigm shift underscores the convergence of cyber-physical systems with socioeconomic ecosystems, redefining traditional boundaries between human and machine roles in production and economic management.

Based on the evidence reviewed above, we posit two hypotheses:

H1: The evolution of social networks, considering physical (driven by urbanization) and virtual (based on Internet usage) spaces, significantly shapes how countries generate wealth.

H2: The relationship between physical and virtual networks has shifted: The Internet now plays a more dominant role in wealth creation than urbanization, which was the primary driver in earlier industrial revolutions.

This study explicitly accounts for the transformative potential of emerging technologies when analyzing the effects of virtual (Internet-based) and physical (urbanization-driven) social networks on wealth creation. The digital and urban networks' impact on countries' wealth integrates the established principle that technological supremacy drives economic hegemony (Atluri & Dietz, 2023; Baldwin, 2019). Nevertheless, countries' economic outcomes are more complex than the sum of their inputs. There is an aetiology of the relationships between actions and results that is linked to a dynamic and complex context.

In the 19th century, China's economic supremacy was devastated by the Opium Wars, suffering the consequences of an addictive substance that it produced and knew like no other country (Hanes III & Sanello, 2004). Metaphorically, the West could compromise its economic development, in a technological and virtual myopia, which stylizes the human into a Leonardo da Vinci Vitruvian Man, always in harmony with the Universe. There is a mainstream thinking where regular virtual spaces overlook irregular physical boundaries (Graham, 1998; Zook & Graham, 2007). Everyone wants to be on the Internet, creating new networks, just like the social networks created at the beginning of the First Industrial Revolution, with cities growing around the manufacturing industry (Beniger, 2009; Castells, 2010). The societal and economic impacts of digital technology adoption differ fundamentally from those of technological mastery. Using technology is different from getting wealthy through technology.

Under globalization, Western countries systematically offshored manufacturing capacity to Asia, especially China, while transferring technical knowledge - a strategic oversight that has allowed the rise of competitive economic challengers to traditional Western dominance (Baldwin, 2016; Lee, 2022).

Assuming previous evidence, the following, third, hypothesis is advanced:

H3: China's economic growth trajectory has not yet approached its theoretical maximum capacity.

This last hypothesis attempts to unravel the challenges that Western economies face due to the economic inertia of China, which is increasingly emerging as a relevant actor in the *status quo* of the world economy.

Despite the increasing share of services in the global economy (Lábaj & Majzlíková, 2022),

there are no countries that have services without products. Nowadays, China leads the production of devices for the Internet of Things, which, considering its population, size, educational level, scientific advances, and technological development, emerges as a notable economic competitor against the USA, Japan, and Europe (Jiang & Murmann, 2022).

After this introduction, to answer the research question, the paper follows with 2) the relationship between social networks and technological and economic development; 3) presentation of the selection and data collection criteria, their temporal and spatial dimensions, characterizing the population under study; 4) search for a pattern that reveals the complexity of data relationships, to develop mathematical theories that model the relationships between different variables; 5) selection and validation of the mathematical model that allowed extracting indicators from the data revealing the dynamics of the complexity of the relationships between the different variables; 6) analysis of the results obtained and answer to the research question; and 7) conclusions highlighting the results that answer the research question, the most relevant new scientific contributions and future research proposals.

2. Social networks in technological and economic development

Literature has reduced social networks to digital/virtual space when the term precedes technology and the virtualization of spaces (Castells, 2010). Since the beginning, humans have subsisted through social networks. Thus, physical (natural) or digital/virtual environments can support social networks, which, despite being human-based, can incorporate other agents. Networks expand and increase their complexity, and some agents may be other networks, which support collective intelligences, composed of human and/or artificial agents (Rainie & Wellman, 2012). When referring to social networks, it is essential to indicate the environment in which they develop: physical, digital, or hybrid (cyberphysical).

The first industrial revolution emerged from the productive potential of physical social networks, with cities growing around factories, creating a synergistic environment that fostered the productive effect of social networks and economic growth. Until the Great Depression of 1929, economic growth depended on the quantity produced – the market grew with supply. Before the global crisis, the world had already witnessed two industrial revolutions using tools provided by mechanics and electricity. After the social and political readjustment of the Second World War, electronic computing emerged, providing the third industrial revolution, where processes are automated. The third industrial revolution was a potential element of Globalization because the technologies involved allowed a rapid transfer of automated production systems. Until the beginning of the 21st century, social networks prioritized physical space, and the economy took place where humans were. However, the Internet creates an environment conducive to social interaction, and social networks expand into the virtual space, which, although previously exploited in manufacturing in the late 20th century, gained new momentum with Cyber-Physical Systems and Industry 4.0 in the second decade of the 21st century. Humans have created connections on the Internet and use it to conduct, control, connect, communicate, collaborate, contribute, create, consume, or crave. It is a comprehensive environment that encompasses deep rational and emotional behaviors. The results will depend on the use (Zuboff, 2019).

Depending on the context and intent, social networks continue to have a major impact on economies, manufacturing, advertising, and consumption systems. The context is dynamic and transitory. Its nature is cyberphysical and interferes differently in the economies of

countries. Without overcoming the asymmetry in the creation and consumption of knowledge generated by and in networks, without a culture that promotes intelligent and sustainable technological development, with the advancement of digital technologies, differences in the social and economic development of countries around the world will increase (Matkovskaya, Ekimova, & Kuznetsov, 2022).

The reduction of social and economic asymmetries involves a paradoxical situation. Technological advances and increased efficiency provided by Industry 4.0, which are significant for the economy, still do not fully address social needs (Pinheiro et al., 2021). Societies that are less technologically developed require the introduction of "smart" technologies in environments marked by poor socio-economic development and deep dissatisfaction with the quality of life. Nevertheless, people are more concerned with low incomes and rising prices than with integrating smart technologies (Volkov et al., 2023). This underscores the importance of the quality of public administration in achieving results from the adoption of new technologies (Volkov et al., 2023), as well as the role of social networks in technology use, knowledge production, and economic growth. Networks foster innovation, knowledge sharing, and support organisational learning both internally and externally (Miković et al., 2023), which is vital for the development of resource-constrained countries.

Social, economic, technological, and scientific systems influence each other (Pinheiro et al., 2019). Nevertheless, there still persists in the scientific community a fatalistic perception that, due to their dominance of technology, developed countries limit the economic growth of developing countries and that, furthermore, inequalities tend to increase (Santos et al., 2022). However, technology is just a tool, part of a much more complex context. Although within countries this economic inequality may have increased, with the United States in the group of most unequal countries (The World Bank Group, 2024), the figures show that since 2000, inequality between countries has decreased (Gradín, 2024).

Industrial revolutions were often followed by significant social and political changes. Changes are likely to occur that establish interoperability and intensify the use of new technologies across complex and diverse platforms, both digital and traditional (Stefanovic et al., 2024). Despite technological development, no production system can prevail in the face of disruptions created by unforeseen events caused by system failures and crises (Sozinova et al., 2023).

Human relationships are increasingly based on virtual social networks. Physical connections are becoming virtual in different human contexts (social, economic, manufacturing, services, etc.). Behavior change and wealth development are interconnected; business follows people, and people follow business. If one enters the virtual space, the other tries to take advantage and follows suit, adopting virtual social connections and dynamic reconfigurability (Putnik et al., 2020).

3. Selection and data collection

Data were extracted from Our World in Data (2024a, 2024b, 2025a, 2025b), which aggregated data from the World Bank (The World Bank Group, 2025), the United Nations World Population Prospects (United Nations, 2018). Countries with fewer than 200k inhabitants were excluded from the study. When data was unavailable for a given year, it was interpolated or extrapolated depending on its position in the database. Thus, this paper considers the behavior of GDP per capita, Purchasing Power Parity (PPP) (constant 2021 international $), of 172 countries, between 24 years (from 2000 to 2023), considering Internet usage and urbanization.

Given that countries have different populations and to ensure consistency in the analysis of results, all variables are converted to *per capita*, dividing the absolute values of the population using the internet and the population living in urban areas by the population of each country. All error computations will be weighted considering the different data populations under study. All simulations were made in Python.

Figure 1 shows GDP per capita versus the Internet usage index and urbanization index of countries in 2023. The size of the points is proportional to the population, with some countries standing out, such as India and China. Considering the GDP per capita, the United States stands out above all other countries presented in Figure 1.

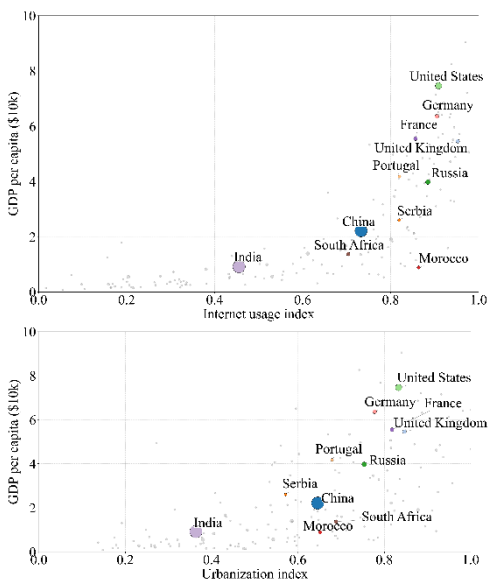

Figure 1. GDP per capita regarding the Internet usage index (at top), and the urbanization index (at bottom), in 2023.

4. Models for GDP per capita through Internet usage and urbanization

Although the 2023 data suggest an exponential distribution of GDP per capita in both cases of Internet usage and urbanization, an assessment of the coefficient of determination (R^2) was made considering linear, exponential, and power-law weighted regressions for the period between 2000 and 2023. Figure 2 shows the values obtained for R^2.

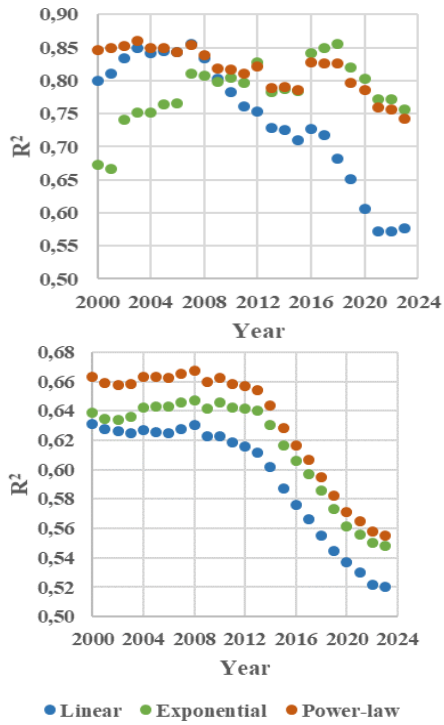

Figure 2. R^2 values for the linear, exponential, and power-law weighted regressions of GDP per capita function of Internet usage (at top), and urbanization (at bottom), between 2000 and 2023.

The R^2 values suggest that the countries' GDP per capita fits better to the power-law and exponential distributions than to the linear one, for the entire study period in the case of urbanization and from 2008 onwards in the case of Internet usage.

Considering the R^2 values in Figure 2, it is more likely that countries' wealth creation depends on a function belonging to the exponential or power-law family when we compute it considering Internet usage and urbanization. Thus, the fitting of Equations 1, 2, 3, and 4 to the GDP per capita is assessed.

Equations 1 and 2 relate two power-law functions, while equations 3 and 4 consider two exponential functions to describe the wealth creation. Hybrid models with both power-law and exponential distributions are not used, allowing a comparison of the Internet usage and urbanization, and knowing which is more significant in GDP per capita.

$$W = cI^a + dU^b \quad (1)$$

$$W = cI^a U^b \quad (2)$$

$$W = ca^I + db^U \quad (3)$$

$$W = ca^I b^U \quad (4)$$

Where, considering each country:

W is the modelled wealth created per person, listed as GDP per capita, at purchasing power parity, in 2021 (in US dollars);

I is the Internet usage index, with values between 0 and 1, from the ratio between the population that used the Internet in the last three months and the total population;

U is the urbanization index that indicates the level of urban population concerning the total population, with values between 0 (only rural population) and 1 (only urban population);

a and *b* are dimensionless parameters that characterize the models, depending on whether exponential or power-law distributions are considered;

c and *d* are constants of proportionality needed to ensure that the equation is dimensionally consistent (in US dollars).

5. Choosing the model that best fits the complex pattern of GDP per capita

To assess which of the equations best models the behavior of GDP per capita, we use the Mean Absolute Percentual Error (MAPE) and the Weighted Least Squares (WLS). In the computation of both approaches, Equation 2 best adjusts countries' real GDP per capita.

Figure 3 shows the R^2 values of Equation 2 in the case of MAPE and WLS.

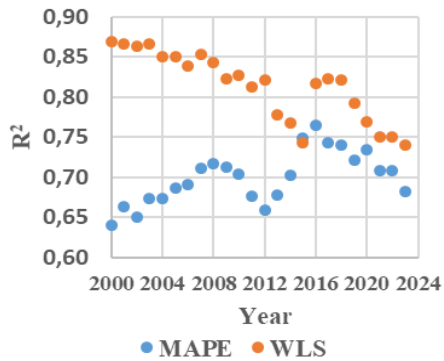

Figure 3. R^2 values considering MAPE and WLS, between 2000 and 2023

Since, except for 2015, the WLS achieved higher R^2 values, the values of *a*, *b*, and *c* from the model calculation using the WLS were chosen. The values of *a*, *b*, and *c* are shown in Figure 4.

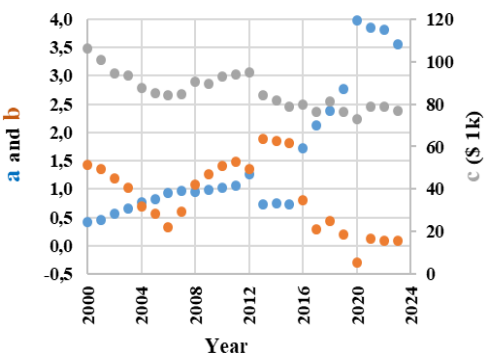

Figure 4. Values of *a*, *b*, and *c* for the equation $W = cI^a U^b$ modeled by WLS

Considering the previous computations, it becomes possible to compare the graph relating real GDP per capita to Internet usage and urbanization with the model resulting from Equation 2. Figure 5 shows the graphs concerning the real data and the simulated values resulting from Figure 4.

Figure 5 illustrates the GDP per capita trends for 172 countries over the 24 years from 2000 to 2023, with the size of each point reflecting the population of each country. Examining

the graphs, the population sizes of China and India are prominent, along with a decrease in the variability of GDP per capita values in the model, particularly when considering values exceeding $50k.

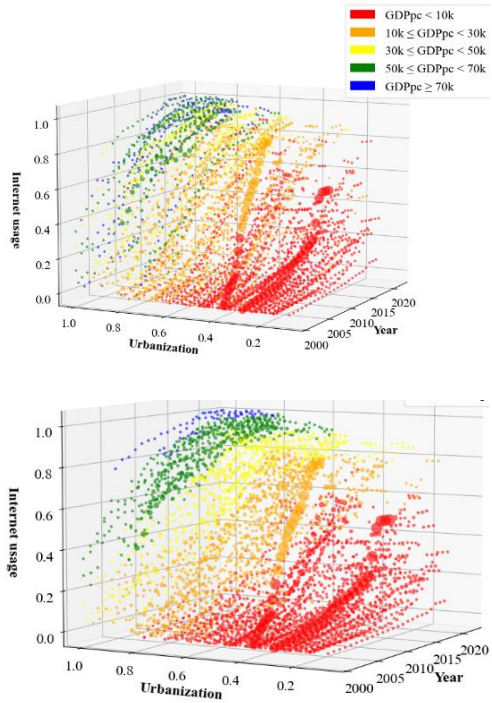

Figure 5. GDP per capita performance regarding Internet usage and urbanization, assuming real data (at top) and the model (at bottom), between 2000 and 2023.

6. Findings

Figure 4 shows that after 2012, concerning the countries' GDP, the relationship between Internet usage and urbanization indices is opposite, signaling that countries use some kind of networks as long as the benefits of the interaction in a space, physical or virtual, outweigh those of another. This kind of behavior is similar to the observed in nature, e.g., most pollinators, for instance, will abandon a plant species discover a higher quantity or quality of nectar elsewhere (Bronstein, 1994). Thus, the emergence or dissipation of collective behavior in the networks depends on rewards (Holland, Deangelis, & Bronstein, 2002) - if they are perceived as worse than the alternatives, the network shall dissipate; if they are perceived as better than the alternatives, then the network shall expand.

Often, symbiosis enables the dismissal of one of the parts if it is beneficial to the majority, even if it conditions the sustainability, seeking the efficiency of the whole system. On the other hand, synergetic behaviour intends to improve the system's resilience, where the outcomes are different from the sum of the parts that compose the system. Synergistic effects are ubiquitous. They show how economic systems are braided, like a brain structure, unveiling parts together into a consciously perceived and meaningful whole (Corning, 2003).

According to the synergy meaning assignment, the model that best describes the economy with Internet usage and urbanization as input variables is synergistic, represented in Equation 2, and not symbiotic (revealed in Equation 1), because it results from a multiplication of non-linear effects. Synergy is usually represented by multiplication or even exponential functions, embodying a collaborative interaction where the combined effect is amplified. Synergy often trumps symbiosis, the results of which are the sum of the individual contributions of the system.

From the model, we consider that the values of a and b, from Equation 2, applied as exponents in two variables (Internet usage and urbanization) whose values vary between 0 and 1, can frame 3 meanings:

- The closer the exponent a or b is to zero, the indicator shows that the economy's performance is more dependent on the other variable, given that any number raised to the power of zero is one. When the value is below zero, it means that the existence of the network is detrimental to the production of wealth.

- The closer *a* or *b* is to the value 1, the more synergistic the effect will be, proportional to the value of the variables associated with these indicators.
- The higher the value of *a* or *b*, the more damaging the effects on the economy caused by the variables whose indicators (*a* or *b*) are associated.

It can be seen in Figure 4 that the evolution of *a* and *b*, in the periods between 2000 and 2006 and between 2016 and 2023, is complementary, that is, when *a* goes up, *b* goes down, and vice versa. It is noted that the negative value of *b* in 2020 and as a result of the COVID-19 pandemic, made urbanization a negative aspect for wealth creation in countries. On the contrary, the higher value of the indicator *a* in 2020 reveals that countries that were not represented on the Internet saw their economies severely damaged.

From the graph in Figure 4 and considering Equation 2, it can be seen that there is a reduction in the value of *c*. Considering that the value of global GDP per capita grew between 2000 and 2023, we can infer that there is a reduction in inequality in the distribution of world wealth. This finding follows Chancel et al. (2022), which increases the confidence in the results achieved with the model of Equation 2.

Observing Figure 5, we can see that countries with a high urbanization rate tend to have a high Internet usage rate in 2023. This suggests that the gains achieved through physical networks have been transferred to virtual social networks.

China still has potential for growth in urbanization rate and Internet usage (respectively 64.6% and 73.3%, as shown in Figure 1), which is validated in Figure 5, considering real and simulated GDP data from 172 countries. Between 2000 and 2023, China achieved significant wealth growth compared to India, both countries with over 1 billion inhabitants.

7. Conclusions

This paper highlights that humans are more likely to collaborate in a virtual network when they first collaborated in a physical network. Thus, we distinguish the state of being from the action of collaborating in the network. For example, when analyzing, in 2023, the time spent per day by each internet user in South Africa was more than 9 hours, while in Japan it was less than 4 hours, and in Denmark and Germany it was around 5 hours (DataReportal, 2023). Considering that South Africa in 2023 had a GDP per capita of $20,000 (The World Bank Group, 2025) and an Internet usage rate of 0.4 (Our World in Data, 2025b), while Germany and Japan had a GDP per capita of $55,000 and $49,000 (The World Bank Group, 2025) and an Internet usage rate of 0.95 and 0.88 (Our World in Data, 2025b), respectively, staying online for a long time does not mean collaborating and producing on the network. Being only in the virtual world can, on the contrary, become an addiction that limits wealth creation. We are, therefore, in a technological transition that creates new spaces and networks in the virtual world, driven by the Internet (and related tools such as machine learning, cloud computing, blockchain), where those who manage the network domains will have enormous supremacy over others, just as the United Kingdom had over China during the Opium War.

The results indicate that both urbanization and Internet usage have a great influence on the economic development of countries. The spread of the Internet still has immense virtual dimensions of expansion. While physical space is limited by borders (in addition to geographic ones, there are economic, political, and cultural ones), virtual space is fragmented, decentralized, and eminently open. Therefore, we do not advocate a devaluation of the potential of virtual networks (dependent on social networks established on the Internet)

compared to social networks in physical spaces, because this analysis did not verify the time spent on these networks. One hypothesis to explore in future work is the impact of using virtual space on the GDP per capita of territories, considering that the time needed to produce economic value added in the virtual world reduces the time available for humans to interact directly in the physical world.

The results show that the synergistic effect of social networks is a key factor in the economic development of countries. We demonstrate Hypothesis 1 through Equation 2 and Figure 5: The evolution of social networks, considering physical spaces (driven by urbanization) and virtual spaces (based on Internet usage), significantly shapes how countries generate wealth.

The variation of parameters *a* and *b*, between 2000 and 2023, confirms Hypothesis 2 - the Internet now plays a more dominant role than urbanization in creating countries' wealth. Furthermore, with only 73.3% of China's population using the Internet, we confirm Hypothesis 3 – China's economic growth is still far from its potential, considering the Equation 2 model.

The model can be improved by adding other variables, i.e., related to energy, geography, environment, society, politics, culture, and education. To improve the model of Equation 2, part of the research could be abducted and the GDP per capita curve divided into periods between global crises (for example, the American subprime mortgage crisis that contributed to the global financial crisis of 2007-2008, or the COVID-19 pandemic), as proposed in the work of Putnik et al (2024). This approach can emphasize periods of symbiosis that were not observed in this paper, without impeding an evaluation of the results.

Considering the exceptional nature of the crisis caused by the COVID-19 pandemic, the model in Equation 2 should be tested for the years 2024 and 2025 to observe whether the slight degradation in the potential for wealth creation through virtual social networks remains (demonstrated by the reduction in the value of a between 2020 and 2023). If the values of a continue to be quite high, then COVID-19 has triggered the fourth industrial revolution, radically changing social and economic processes, as previously proposed by the introduction of Cyber-Physical Systems and Industry 4.0.

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