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Using Big Data Analysis in increasing transportation infrastructure resilience

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Abstract

Transportation infrastructure plays a vital role in supporting economic activity and ensuring the resilience of communities. This study examines the interconnection of socio-economic effects and the transportation infrastructure resilience in a country in the context of possible disruptions. The results of the study suggest that exploring the relevant socio-economic indicators and monitoring them might help increasing transportation infrastructure resilience by reducing the impact of disruptions on economic activity and improving access to essential goods and services. Additionally, the study finds that the socio-economic effects of transportation infrastructure are complex and multifaceted, and that a comprehensive approach is needed to fully understand and address the challenges posed by disruptions to transportation systems. Overall, the study emphasizes the importance of transportation infrastructure for community resilience and highlights the need for continued investment in this critical infrastructure.

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Keywords: transportation infrastructure, resilience, big data, economic indicators, GDP per capita

1. Introduction

Management science and informatics are playing a crucial role in the transportation industry by providing new tools and technologies to improve efficiency, safety, and sustainability. The integration of advanced analytics, simulation tools, and IoT devices enables transportation managers to analyze large amounts of data on traffic patterns and vehicle movements to optimize routes, predict future traffic patterns and identify bottlenecks (Medyakova et al, 2020; Kurth et al, 2020; Papadopoulos et al, 2017). Furthermore, the use of IoT and big data analytics are also providing new

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opportunities to improve the safety and security of transportation systems. Overall, the integration of management science and informatics in transportation is helping to shape the future of the industry and make it more efficient, safe and sustainable. The paper is structured as follows. First, we deal with the theoretical background of the topic to define the research gap. Then the used data and methodology will be introduced, how the analysis was carried out and the research limitations of the study will be pointed out. In the Results section the outcomes of the data analysis will be presented. In the Conclusions chapter the interpretation of the results and consequences drawn will be summarized, as well as the future research directions will be shown.

2. Theoretical background

Transportation infrastructure is vital for supporting the economic and social well-being of a society, as it facilitates the movement of goods and people through physical facilities, networks, and systems (ITF, 2021). It is critical for the efficient functioning of supply chains and providing access to essential services like education and healthcare, which contribute to an overall higher quality of life (European Union, 2008). Therefore, maintaining and developing transportation infrastructure is essential for continued growth and prosperity.

2.1 Role of transportation infrastructure in national economies

Transportation networks are crucial for maintaining supply chain security, supporting economic growth, and increasing the resilience of critical infrastructure (Kurth et al, 2020). Disruptions to transportation networks can come from natural disasters, political conflicts, cyberattacks, and inefficient logistics, among other sources (Haimes et al, 2002). There are currently various approaches to identifying threats to transport infrastructure, but most of these focus on a single mode or specific threats, rather than an integrated set of all types of threats to multimodal transport infrastructure (Hallegatte, 2019). This is important for maintaining the security and continuity of supply chains, and for supporting economic activity (Alcaraz and Zeadally, 2015). A well-developed transportation system can provide backup options in case of disruptions to one mode of transport. Some existing research has developed models combining economic impact and urban traffic network simulation to measure resilience in transportation networks (Nipa and Kermanshachi, 2021

Supply chain disruptions can stem from natural disasters like earthquakes and hurricanes, political conflicts, labor strikes, health pandemics such as COVID-19, and cyberattacks on transportation and logistics systems (Tonn et al, 2019). Inefficient logistics, including transportation bottlenecks, can also have disruptive effects.

Currently, there are many different approaches to identify threats specific to transport infrastructure. Most of these approaches focus on a single mode or on specific threats, and there is no integrated set of all types of threats concerning the multimodal transport infrastructure in Europe (Jałowiec et al, 2021). Existing research explores and mitigates the effects of adverse events on transportation infrastructure. Economic impact and urban traffic network simulation models, such as those developed by Kurth et al (2020) and Balakrishnan et al (2022), consider the impact of resilience on travel times.

This paper aims to identify ties between transportation infrastructure disruptions and their effects on various socio-economic indicators (Balakrishnan et al, 2022; Lee et al, 2012; Dey et al, 2022). An effective transportation system can help to strengthen the national capabilities of a country by enabling the efficient movement of goods and people, and by providing backup options in case of disruptions (Medyakova et al, 2019; Modgil et al, 2021). This can increase the resilience of critical infrastructure and enhance the overall stability and security of the country (Szyliowicz, 2013; Srinivasa, 2022). The Liner shipping bilateral connectivity index (LSBC)will be applied to measure traffic flow and GDP per capita as a ratio indicator to track the real performance of individual countries' economies.

2.2 Role of Big data analysis in disruption prevention

Information sharing is a widely used mechanism for coordinating supply chains, which can increase competitiveness by providing appropriate information to actors (Mentzer et al. 2001), together with appropriate risk control (Shamala et al. 2017). Quality information sharing can also aid in appropriate risk control and extensive data analysis can predict and mitigate the risks of adverse events and threats (Osmólski et al, 2019). However, the creation of big data in multiple organizational processes with high variety, volume, and velocity exceeds the capabilities of traditional data processing systems. Thus, big data analysis (BDA) incorporates not only technologies but also skills and practices to structure and process data to provide useful information for decision-makers.

The BDA can play a crucial role in enhancing the resilience of supply chains (Wang et al. 2016). Papadopoulos et al. (2017) stated that Big Data has great potential to optimize recovery strategies and is a big help in supply network management. By providing a deep understanding of changes in the business and market environment, companies can be better prepared for disruptions (Bahrami and Shokouhyar, 2021). With the help of data analytics and machine learning algorithms, potential supply chain disruptions, such as transportation delays, supplier issues, or natural disasters, can be identified before they occur (Demeter et al. 2020). This allows companies to take proactive actions to mitigate the impact and ensure the continued flow of goods and materials. Additionally, a bibliometric analysis revealed that most academic papers addressing supply chain disruption issues focus on managing and designing the network to achieve resilience (Nagy et al, 2022).

To deal with difficult situations, developing the analytical capabilities of supply chains and placing a strong emphasis on capturing the knowledge from the network, and improving decision-making capacity allow the chain to operate in a resilient way (Modgil et al, 2021; Dujak et al, 2019). There is a strong need for building BDA systems capable of filtering, and analyzing data from various sources, in large volumes, variety (Demeter et al. 2020). Infrastructure, and staff expertise are needed to use BDA to the proper standard (Wamba et al, 2017).

2.3 Research gap

After reviewing the literature, the authors found that several research gaps can be identified in the application of big data analytics in transportation infrastructure disruption prediction. First, there are ties between the disruptions and the economic consequences, but no structured analysis exists yet about how and what is interconnected, what are the drivers of economic consequences if there is a transportation network disruption.

Second, it is also important to research, that which economic indicators are the ones which can reflect immediately - or in short term - the effects of a disruption in the transportation network, and through this can help early identification of possible and appropriate countermeasures. In the following section, the methodology of filling the research gap will be introduced.

3. Goal, Methodology

The identified research gap highlights the potential of big data analysis in improving transportation networks. This technology can enhance traffic management by analyzing data from various sources (e.g. traffic sensors, GPS devices), identifying congestion points and devising strategies to reduce delays. It can also detect maintenance and repair needs proactively, mitigating the risk of major disruptions. Through analyzing diverse data sources, big data analysis can predict and prevent disruptions, such as accidents or equipment failures, and improve safety by identifying accident hotspots and implementing targeted interventions. (Yusta et al, 2011).

To improve transportation planning and overcome these challenges, businesses can utilize data-driven tools and technologies (Nagy et al, 2022). By analyzing data on transportation routes, schedules, and potential disruptions, companies can adjust their plans to minimize delays and ensure timely delivery of goods and materials. With the help of data-driven tools and technologies, businesses can improve the efficiency and reliability of their transportation planning, resulting in fewer disruptions and improved performance of the supply chain (ITF, 2021).

3.1 Research goal

The research aim is to investigate the potential influence of the disruptions on the transportation infrastructure and the strength of possible ties between them and various socio-economic indicators of a country, including immediate and short-term effects. The main research question is: "What are the ties between the transportation disruptions and economic consequences?". Furthermore, a value-added by this paper will be to identify measures for transportation infrastructure performance, and also, those socio-economic indicators which are the most relevant in signaling the effects of transportation network disruption at an early stage. This identification of the possible ties could be further used for the prediction models to prepare and react on the possible disruptive events.

3.2 Methodology

Big data analysis can be used in the development of future models of transportation infrastructure by analyzing data on transportation patterns and trends, companies and infrastructure operators to better understand how people and goods are moving. BDA can be used to forecast future demand for transportation services, and can be used as a powerful tool for supporting the development of future transportation infrastructure models and future investments.

The presented research investigates the possible approach of applying free access data concerning transportation network/transport availability and economic indicators to trace the consequences of transportation infrastructure disruptions. The steps of the research were as follows:

1. Based on GDP per capita (p.c.) data, clusters were created from the countries with similar annual changes in the period of 1960-2021.
2. Cluster analysis on GDP p.c. produced clusters with four main representing areas and for each cluster four representative countries were defined.
3. As a next step, the quarterly data of the LSBC index was collected, and from whole dataset consisting of 1 640 656 values only those were analyzed further which belong to the 16 representative countries (4 from each 4 clusters).
4. From quarterly LSBC index an annual average value was created for each country for each year.
5. For each cluster an average annual LSBC index was created by averaging the values of the four representative countries.
6. Similarly, from the GDP p.c. annual changes data an average was created for each year, based on the data of the four representative countries.
7. A comparison of trends in cases of LSBC index and GDP p.c. changes was carried for the four clusters, making visible by graphs the main infrastructure disruption events, which were global financial crisis 2008-2009, Hanjin Shg bankruptcy 2016, and Covid-19 pandemic 2020.
8. The comparison of the changes of LSBC indices and GDP p.c. in selected periods are presented in Figure 2.

4. Analysis and Data

In Step 1, cluster analysis was carried out based on the data of GDP p.c. annual changes of countries. The hierarchical and K-mean cluster analyses in the Orange data analysis software produced five clusters which of one rather contains outliers so in the followings the four main clusters will be further analyzed. The output of the cluster analysis presenting the concentration of similar countries in GDP p.c. annual change is shown in Figure1.

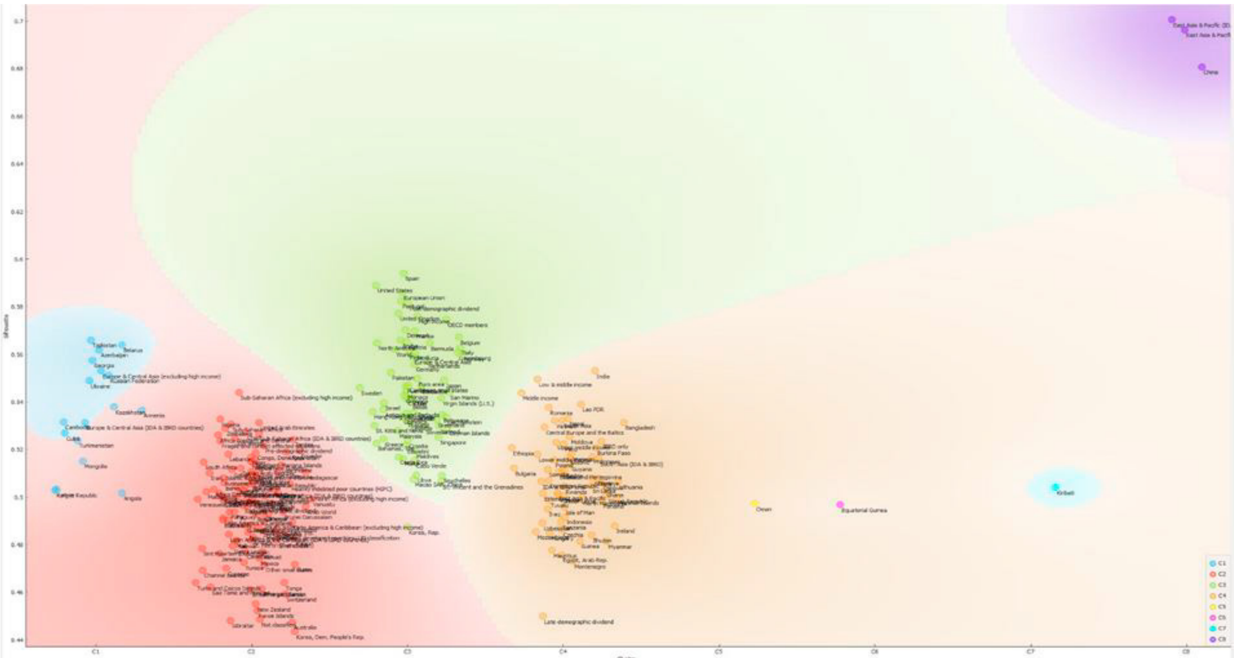
As Step 2 four representative countries were selected from the main clusters (C1, C2, C3, C4). From the four main clusters and their centroid, the following countries were randomly selected:

- C1: Cambogia, Georgia, Russian Federation, Ukraine;
- C2: Tunisia, Venezuela, Iran, Mexico;
- C3: Denmark, Belgium, Italy, Netherlands;
- C4: Peru, Vietnam, Poland, Philippines.

In Step 3, LSBC's quarterly data were collected from the database for those 16 countries which were selected for further analysis (See in Appendix 1). LSBC index indicates a country's integration level into global liner shipping networks and creates the countries´ overview of their transport connectivity as a crucial determinant of exports (UNCTD, 2023).

In Step 4, in order to structure the data and then being able to compare LSBC index data with annual changes of GDP p.c. the quarterly LSBC data were aggregated to annual data by making an average from the four quarterly values.

During Step 5 and 6, for both LSBC and GDP p.c.-change, the values of the four representative countries were summed up and a common value (average) was produced to represent the cluster. These cluster-typical LSBC index data and GDP p.c. change data were used to find ties between the transportation and economic performance indicators (Figure 2).



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The graphs show the correlation of the average LSBC with the average GDP p.c. In case of countries in the C1 cluster, i.e. countries with a lower level of average LSBC, there is a higher fluctuation of the average LSBC following external stimuli and distortions in the distribution capacities. In terms of their distribution capacities, these countries are heavily exposed to potential external disruptions to their distribution or logistics capacities, and also their average GDP p.c. annual change is over 3,1%. For these countries it is typical that they are highly dependent on the external economic ties, with limited internal economic capabilities to minimise possible external distributional disruptions.

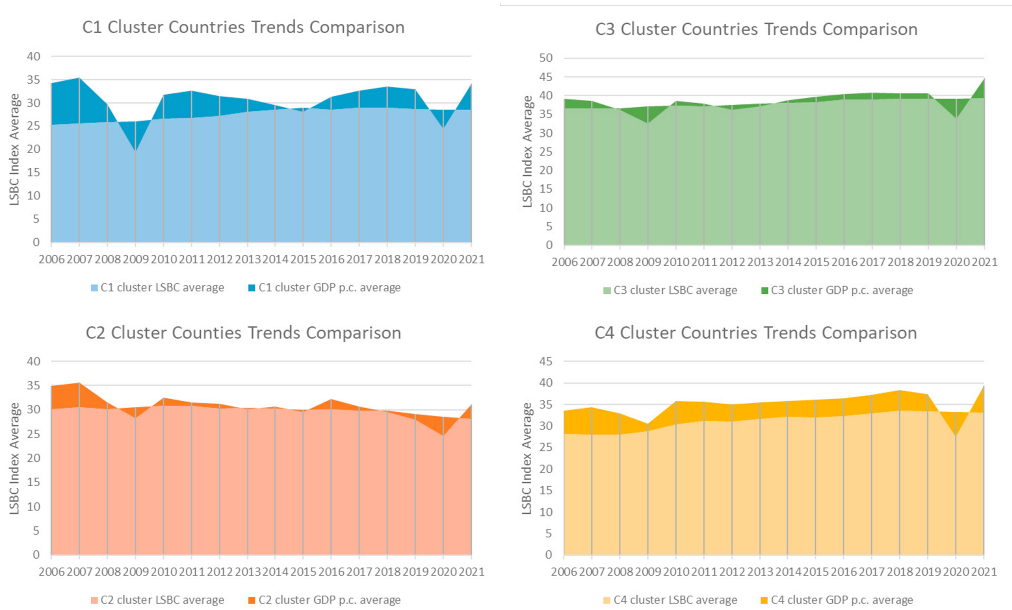

Fig.2. Correspondence between annual GDP p.c. change and LSBC index change (own edition)

Similarly, in the case of C2 cluster countries, it can be seen, that although the average LSBC is higher, it is still below 30%. The year-on-year change in LSBC between 2006 and 2021 was already only slightly above the year-on-year change in GDP p.c., or in the case of the decline between 2009 and 2019-2021, the decline was not as pronounced as in the case of cluster C1 countries. These C2 cluster countries are also highly dependent on external ties, but their economic capabilities could better absorb potential external disruptions.

In the case of cluster C3 countries, with around 37.9% LSBC change over the period of 2006-2021, with an average GDP p.c. change of 0.5%. In case of cluster C3 countries, there is a higher correlation between year-on-year changes in LSBC and GDP p.c., with a stronger interdependence between the two, i.e. transport and distribution capacities respond adequately to changes in economic performance, including experts and imports.

For cluster 4 countries, the annual rate of change in LSBC is 31.2% and the average annual change in GDP p.c. is 3.8%. For these countries, it is evident that their significantly higher growth rates in transport and distribution capacity are relative to the level of annual changes in GDP p.c.

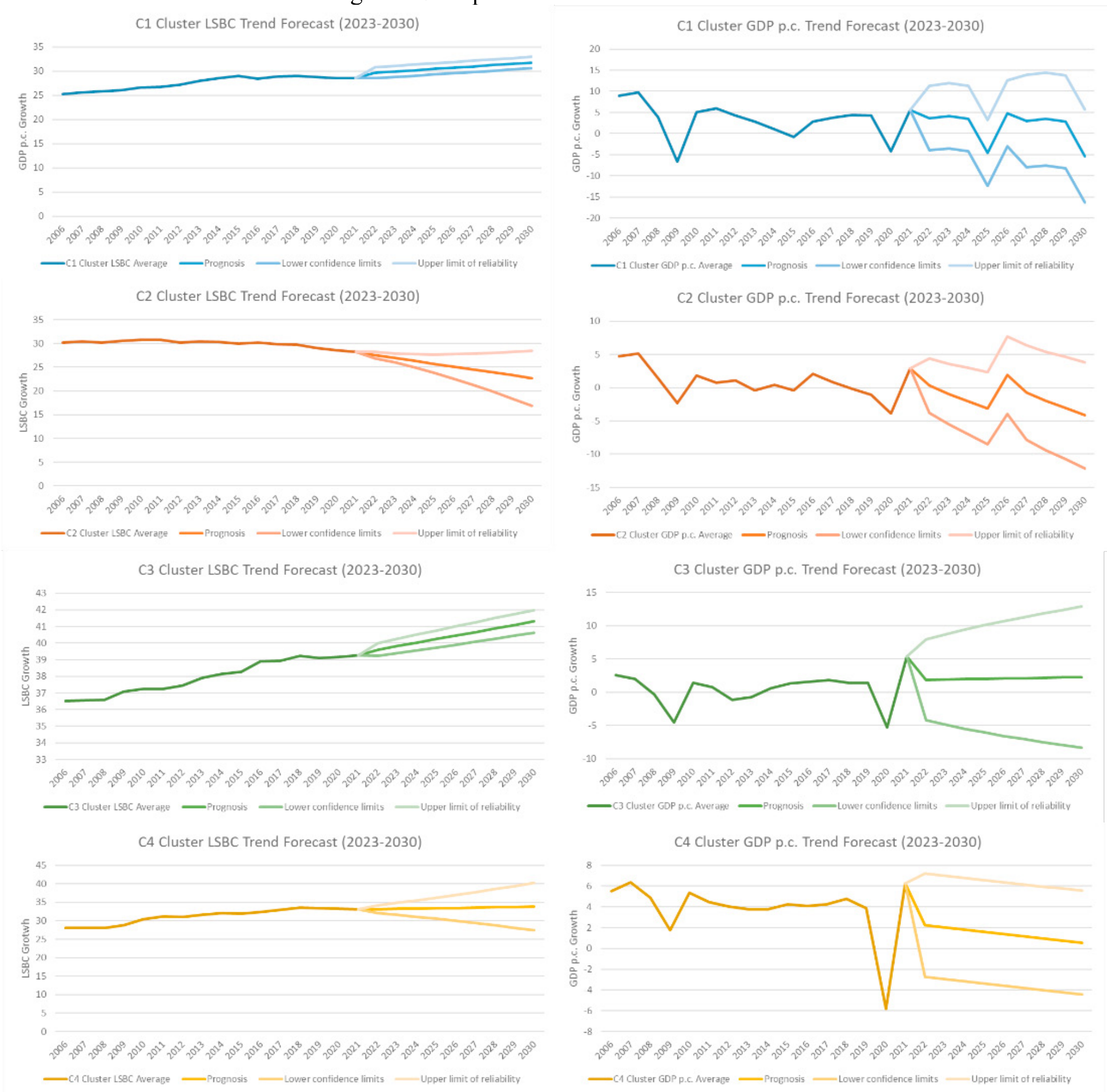

Fig.3. Forecast scenarios for LSBC index and GDP p.c. and their correspondence (own edition)

The analysis of the clusters C1-C4 and the interdependence of LSBC and GDP p.c. in these countries shows a significant sensitivity of logistics capacities in response to economic changes in C1 countries, with the assumption of larger available capacities, which can be considered as redundant, but allowing to absorb external disruptive stimuli. In the case of C2 cluster countries compared to C1, these spare capacities are also available, but to a lesser extent. In the case of C3 countries, the transmission and distribution capacities are at a level commensurate with the performance of the economy and the needs of society, including the ability to absorb potential external disruptions. In the case of C4 countries, transport-distribution capacities are above the economic performance, creating the conditions for significantly open economies.

In the following step (#7) a comparison of trends of changes was observed in case of the four clusters and some possible infrastructure disruption events were identified, like:

- global financial crisis 2008-2009;
- Hanjin Shg bankruptcy 2016;
- Covid-19 pandemic 2020.

In the final Step 8 the changes of LSBC indices and GDP p.c. change in selected periods was analyzed (Figure 3).

Figure 3 shows the forecast scenarios for the LSBC and GDP p.c. indices in accordance with the trends in LSBC and in annual changes in GDP p.c. for the countries associated with the selected clusters. The trends show different sensitivities to economic disruptions and changes in the availability of maritime transport capacity. This divergence is also evident over the further forecast period 2023 to 2030, especially in the variance of the expected values with 95% probability.

To determine future trends in the development of LSBC and GDP p.c. in the clusters of countries C1-C4, the expected possible future is that an increase in transmission and distribution capacities in countries C1 and C3 are visible, with a relative balance of the increase in LSBC. In the case of C2 and C4 countries, there is a downward trend in LSBC. According to the performed classification and development of GDP p.c. it is difficult to predict its future development. For C1 countries, the overall range of future GDP development p.c. approximately 23%, for C2 it is approximately 16%, for C3 approximately 19% and for C4 countries approximately 10%.

The countries representing clusters C1, C3, and C4 show a pro-growth trend, with a very limited range of possible future developments. Only for the countries in cluster C2 a decline in LSBC can be found and a much larger dispersion in the forecasts for the years 2023 to 2030. The trend for GDP p.c., which responds significantly to disruptive changes, is significantly different. For this reason, its future evolution is also difficult to predict and therefore more dispersed.

5. Conclusions

This study examines the relationship between socio-economic effects and transport infrastructure resilience in the event of disruptions. Results show that socio-economic indicators are dependent on transport infrastructure and capacities. Disruptions to transportation have significant impacts on socio-economic indicators with a time delay.

The study grouped countries based on their similar responses to changes in the external environment, including disruptive effects on transport and distribution infrastructure. It is not possible to predict the expected magnitude and timing of disruptions, but the analysis shows the potential to identify individual economies' ability to absorb potential disruptions by making their capacities more robust. The study emphasizes the importance of investing in transport infrastructure to increase its resistance and safety, as it significantly reduces the potential socio-economic impacts of disruptive events. However, a limitation of the study is that LSBC can only be interpreted for countries with access to the sea, so other indices may need to be included in the analysis to measure the change in more relevant attributes of logistics performance in case of a disruptive event.

Other directions of possible research could be the expansion of the sample of the number of countries included in the analysis and the interlinking of individual prediction trends, with the simultaneous evaluation of mutual correlations. It could be interesting to include also landlocked countries without direct connection to see trade rates. This step would refine the entire data set and therefore make possible future predictions more accurate.

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