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LOGISTICS IN THE ERA OF CLIMATE CHANGE: A REVIEW OF CHALLENGES AND DEVELOPMENT OPPORTUNITIES

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Purpose: The aim of the article is to analyze the impact of climate change on the logistics sector and to identify key challenges and opportunities for development in the context of sustainable development. It also discusses the actions being taken by the logistics industry to adapt to new climate conditions, technological innovations, and legal regulations that necessitate the transformation of this sector.
Design/methodology/approach: The article is based on a literature review and current data regarding the impact of climate change on logistics. An overview was conducted of global supply chains, adaptive measures, investments in sustainable infrastructure, and technological innovations. Particular attention was paid to legal regulations related to CO_2 emissions and sustainable development policies that shape logistics strategies.
Findings: Climate change significantly impacts logistics, causing disruptions in supply chains and damage to infrastructure. The logistics sector responds to these challenges through investments in low-emission technologies, the implementation of innovations such as artificial intelligence and warehouse automation, and adaptation to new legal regulations. The analysis indicates that a key element for the industry's survival is flexibility and sustainable development, which enable more effective resource management and adaptation to global trends.
Originality/value: The article provides a comprehensive overview of the latest challenges and innovations in logistics in the context of climate change. In addition to analyzing the impact of these changes on supply chains, it presents innovative technological solutions and legal regulations that are fundamental to the future of the industry. The article emphasizes the importance of international collaboration and adaptation to new market realities, which represents a unique contribution to the discussion on sustainable logistics development.
Keywords: climate change, green logistics, global supply chains, sustainable development.
Category of the paper: literature review.

1. Introduction

In the face of rapid climate change, logistics is confronted with challenges that have not been part of its daily operations until now. With rising global temperatures and increasingly

frequent extreme weather events, the logistics sector finds itself on the front lines, facing the necessity of adapting to a new reality. Floods, droughts, hurricanes, rising sea levels, and other weather phenomena disrupt the functioning of international supply chains, and the impact of these changes is increasingly felt by both companies and consumers. Global climate change is beginning to affect every aspect of logistics operations, from transportation to warehousing, which requires new, more sustainable approaches (Luthra et al., 2018).

Logistics, as a key component of the global economy, plays a crucial role in ensuring the smooth flow of goods and services worldwide. It operates within a complex, multi-layered ecosystem that includes transportation, warehousing, distribution, and resource management (Rebs et al., 2017). The interconnections between these processes mean that any disruptions caused by climatic events can lead to global economic consequences. Phenomena such as blockades of shipping channels, damage to roads, or power supply interruptions can result in delays and increased operational costs. Consequently, climate change directly affects the efficiency of supply chains, and its impact is expected to grow in the coming years (Bhalaji et al., 2024).

In Poland, as well as in other Central European countries, climate change is becoming increasingly evident, particularly in the form of floods, storms, and other weather anomalies. The flood of 2024, currently affecting regions such as Silesian, Opole, and Lower Silesian Voivodeships, is a dramatic example of the scale of destruction that these phenomena can cause. While the full effects of this natural disaster are still being assessed, it is anticipated that the damage will be substantial, impacting transportation and industrial infrastructure that is critical for logistics and economic activity. Floods can lead to supply chain disruptions, damage to roads and bridges, and paralysis of entire regions, necessitating long-term recovery and adaptation to new climate conditions (Achebe et al., 2021).

As the world faces increasingly unpredictable climatic conditions, it is essential for the logistics sector to adopt a proactive approach (Adger et al., 2005). Adapting to climate change, technological innovations, and sustainable development are becoming priorities for companies that aim not only to survive but also to thrive in this new reality. Implementing sustainable solutions, such as low-emission transportation, eco-friendly warehouses, and more flexible supply chains, is no longer merely a matter of improving corporate image but a necessity arising from the new global situation (Dong et al., 2017).

This article presents an overview of the key challenges facing the logistics sector in the era of climate change, as well as possible pathways for development and adaptation. The following sections will discuss important issues such as the impact of climate change on global supply chains, the need for adaptation and sustainable development in logistics, technological innovations that support the resilience of logistics to climate change, and the influence of legal regulations on logistics in the context of climate change. The aim of the article is to demonstrate that despite the serious threats posed by global warming, the logistics sector also has immense opportunities for growth through innovations and sustainable approaches that can ensure greater resilience to future climate challenges.

2. The impact of climate change on global supply chains

Climate change is increasingly impacting global supply chains, disrupting their fluidity and stability. The intensification of extreme weather events, such as hurricanes, droughts, floods, and wildfires, leads to significant delays in the delivery of raw materials, semi-finished products, and finished goods. For many companies, especially those operating on a global scale, the unpredictability of climatic conditions poses a serious threat to the stability and efficiency of their supply chains (Nchofoung, Asongu, 2022).

One of the most direct consequences of climate change is the damage to transportation infrastructure. Extreme weather conditions, such as heavy rainfall, floods, and severe storms, lead to the destruction of roads, bridges, railways, and seaports. In 2017, Hurricane Harvey halted operations at ports in Texas for several weeks, causing global delays in the delivery of oil and chemical raw materials, which are crucial for many industries. Such events demonstrate how vital transportation infrastructure can be severely damaged, impacting supply chains in various parts of the world (Karaduman et al., 2020).

Climate change also affects the availability and prices of raw materials. The increased frequency of droughts and unpredictable weather events impacts agricultural production and the extraction of mineral resources. For example, droughts in agricultural regions of North America or Australia can lead to a drastic decrease in yields, affecting the prices of food products and agricultural goods (Mndawe et al., 2015). Disruptions in production can also trigger a domino effect in global supply chains, increasing production costs and leading to delays in the delivery of finished products (Mitić et al., 2023).

Another significant factor is the threat to ports and shipping routes. Climate warming leads to rising sea levels, which endanger low-lying ports and transportation hubs. Many of the world's largest ports, such as Shanghai, Rotterdam, and New York, are located in areas vulnerable to flooding due to rising water levels. Floods, storms, and other extreme weather events can result in port closures, delays in loading and unloading, and issues with cargo handling. The blockage of these critical points affects the entire global supply system, leading to disrupttions in international trade (de Abreu et al., 2022).

One of the most challenging aspects of climate change is its unpredictability. Even the best risk management systems in logistics become inadequate in the face of rapidly changing climatic conditions. Events such as sudden floods, wildfires, or severe storms, which were once rare, are now occurring more frequently. For logistics companies and supply chain managers, this poses a significant challenge, requiring a more flexible approach to operational planning. Resources must be available in greater quantities and more widely distributed, which increases operational costs and complicates the management of goods flows (Evans et al., 2009).

However, while climate change presents challenges, it also offers opportunities for innovation and structural changes. Companies that invest in sustainable logistics solutions can not only

reduce their carbon footprint but also protect themselves against future disruptions. Innovations such as electric transport fleets, more eco-friendly storage methods, and the development of climate risk management technologies are becoming crucial for building the resilience of supply chains. In the face of climatic uncertainty, more flexible and sustainable logistics systems can provide a competitive advantage in the global market (Dawson, 2014).

In summary, climate change has a multidimensional impact on global supply chains. Disruptions in transportation, issues with access to raw materials, threats to infrastructure, and rising operational costs are becoming everyday challenges that businesses around the world must confront. At the same time, technological advancements and the development of sustainability strategies can present opportunities for companies that are ready to adapt and innovate. In an era of unpredictable climate changes, the only certainty is the need for rapid responses to challenges and the utilization of available opportunities to build more resilient and flexible supply chains.

3. Adaptation and sustainable development in logistics

In the face of rapid climate change, the logistics sector must take action to adapt to new conditions while simultaneously reducing its negative impact on the environment. This industry plays a crucial role in the global economy, and its efficiency and reliability are essential for maintaining the fluidity of supply chains. One of the main challenges thus becomes implementing sustainability strategies that will enable logistics companies not only to survive but also to thrive in an increasingly unpredictable world. Key investments include modern infrastructure, the use of renewable energy, and the implementation of innovative technologies that will aid in adapting to changing climatic conditions (Souza, Santos et al., 2020).

3.1. Investments in climate-resilient infrastructure

Climate change is bringing increasingly frequent and intense weather events that damage traditional transportation infrastructure, such as roads, bridges, ports, and airports. In response to these challenges, the logistics sector must invest in infrastructure resilient to the impacts of climate change (Mallick et al., 2014). Examples include bridges designed to withstand greater flooding or roads with enhanced durability that are resistant to extreme temperature changes (República Federativa de Brasil, 2016).

Modern infrastructure projects must take into account forecasts for future climate threats. An example of such measures is the construction of drainage systems capable of quickly removing excess water from roads and bridges during heavy rainfall. Additionally, ports and airports, which are crucial for international freight transport, must be adequately secured against rising sea levels and intensifying storms. Such investments can help minimize disruptions in the flow

of goods and maintain the stability of supply chains even in the face of natural disasters (Quinn et al., 2018).

3.2. Implementing sustainable solutions

In the face of growing consumer expectations and regulatory requirements, logistics companies are increasingly implementing sustainable solutions. Reducing CO_2 emissions has become a priority from both an environmental and operational cost perspective. One of the key components of sustainable logistics is low-emission transportation. More and more companies are investing in electric vehicle fleets, which emit significantly less carbon dioxide than traditional vehicles powered by fossil fuels. The development of technology related to autonomous vehicles also opens up new possibilities for energy efficiency and the reduction of greenhouse gas emissions (Jens et al., 2021).

Another important step towards sustainable development in logistics is the use of renewable energy. Increasingly, warehouses and logistics centers are being equipped with solar panels or utilizing wind energy, which allows for a reduction in energy consumption from fossil fuels. Sustainable logistics buildings, which are energy-efficient and optimized to minimize energy loss, are becoming the standard in modern supply chain management. Companies implementing such solutions can not only reduce operational costs but also enhance their image in the eyes of consumers and business partners (Sun et al., 2022).

3.3. Technology for adaptation: improved forecasting and route planning

Modern technologies play a crucial role in adapting the logistics sector to climate change. One of the most important tools that can help companies minimize risks associated with natural disasters is the use of advanced weather forecasting systems and data analysis. These technologies enable the prediction of upcoming threats, such as floods, storms, or droughts, allowing for early preparation for these challenges and avoiding the most affected areas (Rowan et al., 2013).

Advanced GPS technologies and fleet management systems enable logistics companies to dynamically plan routes that avoid areas affected by natural disasters. Real-time monitoring of changes in weather conditions and infrastructure status allows for quick responses and adjustments to delivery plans. The development of artificial intelligence and predictive analytics also enhances risk management in supply chains, anticipating not only weather-related threats but also other potential disruptions, such as interruptions in raw material supplies or shifts in international markets (Tanamal et al., 2023).

Technology also plays a crucial role in optimizing internal processes within logistics companies. Through automation and digitization of operations, it is possible to manage resources more efficiently, leading to reduced waste and increased energy efficiency. Smart warehouses,

where processes such as sorting, packing, and inventory management are automated, help companies minimize energy and material consumption while simultaneously enhancing operational efficiency.

4. Technological innovations supporting logistics resilience to climate change

Ongoing climate change compels the logistics sector to adapt and implement modern technologies that not only help reduce the negative environmental impact of economic activities but also enhance the operational resilience of companies. Technological innovations play a key role in creating more flexible and adaptive logistical solutions capable of handling increasingly unpredictable and extreme climate conditions. In this context, artificial intelligence, automation, and modern transportation methods become essential tools in building a future resilient to climate change.

4.1. Artificial intelligence and data analysis in route optimization and resource management

Artificial intelligence (AI) and advanced data analysis systems are becoming invaluable support in managing logistics in the face of dynamic and unpredictable climatic conditions. By applying AI, it is possible to optimize delivery routes in real-time, allowing for the avoidance of regions threatened by natural disasters such as floods, storms, or fires. Intelligent algorithms, by analyzing weather data, traffic intensity, and the state of infrastructure, can dynamically adjust routes, minimizing the risk of delays and reducing fuel consumption, which contributes to lower CO_2 emissions (Aslam et al., 2023).

Resource management systems supported by AI allow logistics companies to better allocate their resources, such as transport fleets, warehouses, and personnel, in response to changing conditions. Automated analysis of large data sets enables the identification of potential threats, such as supply disruptions, changes in resource availability, or sudden shifts in demand for transportation services. As a result, companies can make quick and precise decisions that minimize the risk of losses and downtime. Furthermore, predictive models analyzed by AI allow for forecasting future issues, giving companies time to prepare alternative action plans (Delanoë et al., 2023).

4.2. Automated warehouses and logistics centers resilient to climate change

Automation of warehouses and logistics centers is another key area where technology helps increase the sector's resilience to climate change. Automated warehouse systems, where robots and machines handle most processes such as sorting, packing, and transporting goods, allow

for greater operational efficiency while also reducing energy and resource consumption. In times when climate change can cause unforeseen disruptions, automation ensures continuity of operations, decreasing dependence on external factors such as labor availability and weather-related issues (Alim, Kesen, 2020).

However, it's not just the automation of processes that plays an important role; the design of warehouses and logistics centers with resilience to extreme climatic conditions is also crucial. Modern logistics facilities are built with consideration for risks such as flooding, rising temperatures, and severe storms. Examples of such solutions include buildings with elevated foundations, flood-resistant drainage systems, and photovoltaic installations that provide renewable energy and reduce reliance on the power grid. These investments in infrastructure enable companies to minimize downtime and losses during crisis situations (Bianchi et al., 2023).

4.3. The use of drones and modern transportation technologies

In the face of natural disasters such as floods, landslides, or fires, traditional methods of transporting goods may prove insufficient. In such situations, modern technologies like drones become a key tool in emergency logistics. Drones enable the rapid and efficient transport of small loads to areas affected by disasters that are difficult to reach with conventional vehicles. They can deliver essential products such as medicines, food, or rescue equipment to locations cut off from traditional transport routes, allowing for quick responses in crisis situations (Mishra et al., 2020).

In addition to drones, other innovative technologies, such as autonomous vehicles and aerial transport systems, open up new possibilities for transporting goods in challenging climatic conditions. Autonomous trucks, guided by advanced navigation systems, can travel routes more efficiently and safely, reducing the risk associated with human errors and improving the flow of deliveries. Meanwhile, the development of aerial transport systems, such as Hyperloop, although still in its early stages, represents a potentially groundbreaking solution that could revolutionize freight transport by minimizing the impact of weather phenomena on shipments (Mitropoulos et al., 2021).

5. The impact of legal regulations on logistics in the context of climate change

In response to the growing threats posed by climate change, governments worldwide are implementing increasingly stringent legal regulations aimed at reducing greenhouse gas emissions and promoting sustainable development. For the logistics sector, which plays a key

role in global trade, these new regulations present both challenges and opportunities for innovation. Logistics companies must adapt their strategies to meet evolving requirements, which impacts transportation technologies, resource management, and operational practices.

5.1. CO_2 emission standards and their impact on transportation

One of the most important aspects of regulations related to climate change is the increasingly stringent standards for carbon dioxide (CO_2) emissions and other greenhouse gases. In the European Union (EU), the "Fit for 55" policy aims to reduce greenhouse gas emissions by 55% by 2030 compared to 1990 levels (Ovaere, Proost, 2022). For the logistics sector, this means the necessity to implement modern transportation technologies and transform vehicle fleets to be more environmentally friendly. Many countries have also introduced emission limits for trucks and other delivery vehicles, compelling logistics operators to invest in electric or hybrid vehicles (Brożyna et al., 2023).

In the United States, new emission standards for trucks and buses were introduced in 2022, reducing nitrogen oxide emissions by 90% compared to previous regulations (Singh et al., 2023). These measures aim not only to limit greenhouse gas emissions but also to improve air quality in cities, which are key logistics hubs.

Transportation and logistics companies must now make strategic decisions regarding fleet modernization (Bollinger et al., 2014). The introduction of electric or hydrogen-powered vehicles requires investment in charging infrastructure and appropriate refueling logistics. Although the initial costs of such transformation may be high, the long-term benefits, such as fuel savings and emission reductions, become a key competitive factor in the market.

5.2. Sustainable development policies and the logistics sector

Legal regulations regarding sustainable development go beyond emission standards alone. Increasingly, governments are implementing policies that require companies to report and reduce their carbon footprint. An example of this is the regulations concerning "Green Public Procurement" (GPP) in Europe, which promote ecological criteria when purchasing logistics services. Companies that provide their services to the government must now meet specific environmental standards, which stimulates the development of more sustainable practices (Cheng et al., 2018).

According to European Union regulations, companies are also required to prepare ESG (Environmental, Social, Governance) reports that consider the impact of their operations on the environment. This exerts pressure on logistics companies to adopt more eco-friendly operational strategies, such as minimizing resource and energy consumption and reducing waste. The requirement for transparency in environmental activities serves as an incentive for innovation, and companies that fail to meet these standards may face difficulties in maintaining a competitive position in the market (Berniak-Woźny et al., 2024).

5.3. Examples of regulations in different countries

Countries around the world are adopting various approaches to environmental regulations; however, the trend towards sustainable development is becoming a global standard. In Germany, through the "Climate Protection Program 2030," the government has introduced regulations aimed at reducing emissions from the transport sector by 40–42% by 2030. This includes promoting intermodal transport, which combines different modes of transportation, thereby reducing emissions associated with long-distance freight transport (The Federal Government, 2024).

Meanwhile, China, as the largest emitter of CO_2 in the world (Chen et al., 2024), has implemented ambitious plans to achieve carbon neutrality by 2060. Chinese authorities have introduced regulations promoting the development of electric vehicles and the construction of green transport corridors to reduce emissions from the logistics sector, which heavily relies on road and maritime transport (Rahaman et al., 2022).

In the United States, one of the key legislative actions is the Inflation Reduction Act of 2022, which includes a comprehensive package of tax incentives and grants for investments in low-emission technologies, including freight transportation. This law provides logistics companies with support for modernizing their fleets and implementing renewable energy systems (Bistline et al., 2023).

5.4. International cooperation and global initiatives

Climate change is a global challenge, which is why international cooperation on legal regulations and sustainable development in logistics is becoming increasingly important. A key role in this is played by the Paris Agreement of 2015, which aims to keep the global temperature rise well below 2°C, and preferably to 1.5°C above pre-industrial levels. To achieve these goals, it is necessary to reduce emissions from the transport sector, which is one of the main sources of greenhouse gas emissions (Meinshausen et al., 2022).

For the logistics industry, this means the necessity of collaborating at the international level to standardize technologies and procedures related to eco-friendly transport. The International Maritime Organization (IMO) and the International Air Transport Association (IATA) have introduced regulations aimed at reducing emissions in the maritime and aviation sectors. An example is the so-called IMO 2050 strategy, which aims to reduce CO_2 emissions from maritime transport by at least 50% by 2050 (Lindstad et al., 2023).

Global regulations and initiatives, such as the "Zero Emission Roadmap," require collaboration not only from transport companies but also from manufacturers, logistics operators, and governments to effectively reduce emissions and adapt economic sectors to future challenges.

Legal regulations related to climate change present an increasing challenge for the logistics sector; however, they can also stimulate the development of innovations and eco-friendly technologies. CO_2 emission standards, sustainable development policies, and global initiatives to mitigate climate change compel logistics companies to transform. International cooperation

and investments in modern technologies will be crucial for the future of the industry, which must not only adapt to new realities but also contribute to combating climate change.

6. Conclusion

In the face of increasing challenges related to climate change, the logistics sector is at a turning point. This article presents a range of challenges and development opportunities arising from the dynamically changing environmental and regulatory conditions that directly impact global supply chains. Climate change, such as extreme weather events, causes significant disruptions in logistics, threatening the stability of goods supply at both national and international levels. The example of Poland, where the effects of floods in 2024 are expected to have a long-term impact on infrastructure and logistics operations, illustrates the substantial significance of climate change for the entire industry.

The impact of climate change on global supply chains, particularly in the context of disruptions caused by extreme weather events, highlights the need for more resilient and flexible solutions. Delays in deliveries, infrastructure destruction, and increasing risks in regions critical to global trade prompt companies to invest in sustainable and innovative solutions. As a result, companies must adapt their operational strategies, which not only forces change but also creates new development opportunities.

The adaptation of the logistics sector, including investments in climate-resilient infrastructure, is becoming a key element of survival strategies. Sustainable development, based on low-emission transport technologies, electric vehicles, and renewable energy sources, is not only a response to new regulations but also a necessity that contributes to the long-term profitability and competitiveness of logistics companies. Concurrently, the implementation of advanced technologies such as artificial intelligence, automated warehouses, drones, and monitoring systems helps anticipate and mitigate the effects of extreme weather events, enabling flexible and effective resource management.

However, a key element shaping the logistics sector in the era of climate change is legal regulation. Both CO_2 emission standards and sustainable development requirements force companies to reorganize their supply chains and adapt to more stringent legal requirements. Governments are setting increasingly ambitious emission reduction targets, compelling the logistics sector to undergo technological transformation. Regulations and international agreements, such as the Paris Agreement, encourage companies to invest in environmentally friendly technologies and collaborate at the global level to meet future demands.

In conclusion, the logistics sector faces serious challenges but also unique opportunities in the context of climate change. The implementation of innovative technologies, adaptation

to sustainable operational strategies, and compliance with new legal regulations are crucial elements that will enable logistics companies to survive and grow in the coming decades. Logistics must not only confront the direct impacts of climate change but also become a driver of innovation that will aid in the global fight for a sustainable future.

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