

Title: Towards Sustainable and Resilient Global Value Chains: A Review of the Role of Machine Learning in Managing External Shocks

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Abstract

This paper delves into the potential of machine learning (ML) in bolstering the resilience and sustainability of global value chains, with a specific focus on managing external shocks such as the COVID-19 pandemic and the Suez Canal incident. It discusses how ML can enhance supply chain visibility, risk prediction, and agility, while also addressing the inherent challenges of technology complexity, data privacy, and cultural barriers. The paper underscores the necessity for a proactive mindset, substantial investment in data infrastructure, and comprehensive workforce re-skilling. It concludes by suggesting future research directions, including the expansion of the respondent base and the consideration of additional influencing factors such as organizational culture and management commitment.

Table of Contents

Abstract	2
1. Introduction	4
2. Literature Review	5
2.1 Machine learning implications on supply chain visibility	5
2.2 Implications for Organizational Practices and Sustainability: Leveraging ML to address disruption	6
2.3 Managing Supply Chain Risks (SCRM)	7
3. Key Findings	8
4. Discussion	10
5. Conclusion	12
References	14

1. Introduction

Global value chains (GVCs) have been hailed as a means to increase efficiency and drive economic growth. Yet, they have also become increasingly complex, interdependent, and vulnerable to external shocks. Disruptions such as natural disasters, geopolitical events, and pandemics can cause significant disruptions to GVCs, disrupting production, increasing costs, and reducing profits (Lund et al., 2020). The COVID-19 pandemic and the Suez Canal incident, for instance, highlighted the fragility of global supply chains, as companies struggled to adapt to sudden and unpredictable changes in demand and supply.

To address these challenges, scholars and practitioners have looked to machine learning (ML) as a promising approach to managing external shocks and enhancing the resilience, visibility, and sustainability of GVCs. ML algorithms can help identify patterns and trends that might not be apparent through traditional forecasting methods, provide insights into the procurement relationships between companies, and enhance supply chain visibility, especially during disruptions.

In this paper, the role of machine learning in managing external shocks and enhancing the resilience and sustainability of GVCs is reviewed. The potential of ML algorithms, such as graph neural networks and artificial neural networks, to improve supply chain risk prediction, increase supply chain agility and re-engineering capabilities, and provide insights into the procurement relationships between companies is examined. Additionally, this paper delves into the implications of machine learning on job displacement and workforce re-skilling, emphasizing the importance of preparing the workforce for the transition towards a more data-driven and automated supply chain management environment.

Challenges associated with incorporating machine learning into supply chain management are also explored, and recommendations on how to overcome these challenges to realize the benefits of these technologies are provided. This paper critically analyzes the COVID-19 pandemic and the Suez Canal incident in relation to the role of machine learning in managing external shocks, offering more specific recommendations for businesses to adopt machine learning in supply chain management.

Through this review, a nuanced understanding of the potential of machine learning for enhancing the sustainability and resilience of global value chains is provided, along with a discussion of the barriers and challenges faced by businesses, particularly small and medium-sized enterprises (SMEs), in adopting and implementing these technologies. By acknowledging and addressing these challenges, this paper aims to guide businesses in capitalizing on the benefits offered by machine learning, ensuring their competitive edge in an ever-evolving global market.

2. Literature Review

2.1 Machine learning implications on supply chain visibility

Outsourcing has been a popular business practice due to its cost benefits for manufacturers. However, this has created emergent interdependencies between companies, which have become increasingly complex and scaled over the past two decades (Christopher and Holweg, 2011). Several studies have highlighted the need for improved supply chain visibility to reduce risks and increase responsiveness to disruptions.

The study "A machine learning approach for predicting hidden links in supply chain with graph neural networks" highlights the significance of supply chain visibility in mitigating risks and enhancing responsiveness to disruptions. The authors point out that various approaches have been proposed to improve supply chain visibility, but they have their limitations, including reliance on the willingness and ability of companies to share information, which is often hindered due to confidentiality and lack of incentives to disclose information (Kosasih and Brintrup, 2021). Additionally, Original Equipment Manufacturers (OEM) have no means of verifying supplier survey data, especially when changes occur in the supply chain structure (Kosasih and Brintrup, 2021).

Recently, researchers have experimented with machine learning (ML) technology to infer procurement relationships between companies, known as link prediction. This task presents a desirable improvement upon existing supply chain visibility improvement methods as it mitigates companies' reliance on the explicit disclosure of supply chain members. The use of Graph Neural Networks (GNN) for link prediction presents advantages over traditional approaches as it is fully automated, alleviating the reliance on manual training of algorithms and the explicit encoding of supply chain expertise (Kosasih and Brintrup, 2021). The proposed approach also brings additional knowledge by predicting the existence of hidden links that are physically present yet missing in the dataset. This additional knowledge may help companies understand their supply chain dependencies better, hence increasing visibility into the risks they are exposed to.

In the comprehensive review, "Relational inductive biases, deep learning, and graph networks", Battaglia et al. (2018) highlight the adaptability and versatility of GNNs, allowing them to capture complex patterns and relationships within supply chain networks. The authors discuss that GNNs can not only predict hidden links but also help forecast potential disruptions and manage uncertainties in supply chain management. This capability is particularly valuable in identifying vulnerabilities in the supply chain and enabling companies to take proactive measures to mitigate risks. GNNs are also able to model and analyze dynamic supply chain networks as they evolve over time, thus providing real-time visibility into the supply chain's state (Battaglia et al., 2018). This continuous monitoring allows organizations to respond more effectively to sudden changes or disruptions in the supply chain, reducing the impact on their operations. However, it is important to note that GNNs' success in improving supply chain visibility is contingent upon access to reliable and up-to-date data. Incomplete or outdated data can adversely affect the performance of GNNs, limiting their ability to provide valuable insights and accurate predictions. Consequently, it is crucial for organizations to invest in robust data collection and

management systems to fully harness the potential of GNNs in enhancing supply chain visibility (Battaglia et al., 2018).

2.2 Implications for Organizational Practices and Sustainability: Leveraging ML to address disruption

The COVID-19 pandemic has revealed the challenges that global value chains (GVCs) face in managing disruptions. To stay competitive, businesses must adopt more resilient strategies. Wong and colleagues (2022) examined how machine learning (ML) can help manage disruptions in GVCs. ML, according to the authors, can assist firms in addressing operational challenges and opportunities, understanding relationships, gaining operational visibility, and facilitating decision-making. ML and improved information processing capabilities can significantly increase the adaptive capacity of supply chains in dealing with disturbances, responding to disruptions, and recovering by maintaining continuity of operations.

Wong et al. (2022) claim that ML algorithms like neural networks and support vector machines can address complicated management issues in GVCs and accurately forecast demand with time lags. The authors argue that the forecasting models built using fuzzy logic, neural networks, and data mining are more reliable than traditional models. The use of ML can enhance the agility and re-engineering capabilities of GVCs.

Yang et al. (2022) take this a step further, demonstrating how ML can help businesses address disruptions more effectively by introducing a decision support framework that leverages ML techniques to assess supply chain risks and recommend risk mitigation strategies. By using ML to predict, assess, and respond to disruptions in real-time, organizations can improve their resilience and overall performance (Yang et al., 2022). The study showcases the potential of ML to play a significant role in organizational decision-making processes when addressing supply chain disruptions.

Through technology, scenario planning can assist managers in anticipating expected and worst-case scenarios to ensure supply and demand alignment. ML and analytical tools can help control towers identify situations where disruptions will make it difficult to meet demand. Supply chain visibility is critical for businesses to assess the impact on supply chains during disruptions and take appropriate actions.

Benhamida et al. (2021) offer an example of how ML can help organizations manage inventory more effectively during disruptions. They present a demand forecasting tool for inventory control smart systems that uses ML algorithms to predict future demands accurately. By reducing stockouts and overstock situations, organizations can achieve cost savings and improved customer satisfaction, even in times of uncertainty (Benhamida et al., 2021). This application of ML shows that technology can play a pivotal role in enhancing the resilience of GVCs, particularly in managing disruptions and maintaining operational efficiency.

The study by Wong et al. (2022) highlights the potential benefits of ML for GVCs, especially for small and medium-sized enterprises (SMEs) that lack the knowledge and resources to leverage technology. However, the complexity of ML poses a challenge for SMEs that may not have the

capability and technological infrastructure to undertake technological interventions. Managers must have a proactive, risk-taking, and innovative mindset to fully realize the potential of ML (Dubey et al., 2019). The use of ML requires data, and SMEs must understand and embrace the idea that digital transformation is the way forward.

Wong et al. (2022) recognize some limitations in their study, such as the specific focus on a particular region, which may limit the generalizability of their findings. Future research could expand the sample of respondents and consider other factors that influence technological adoption, such as culture, management commitment, and technological readiness. Future research may also examine disruptions and performance outcomes as moderating factors in the study, as well as policy and governance aspects to help organizations make responsible ML algorithm adoption decisions while addressing security and data privacy concerns that are typical of ML techniques and big-data applications.

2.3 Managing Supply Chain Risks (SCRM)

The use of machine learning algorithms in managing supply chain risks has significant implications for organizational practices. As such, supply chain risk management involves coordinated and collaborative efforts of all parties involved in a supply chain to assess, identify, monitor, and mitigate risks (Baryannis et al., 2018). With the advent of big data analytics and increased computing power, AI techniques such as artificial neural networks and Bayesian networks have been utilized to deal with risk assessment (Tirkolaee et al., 2021).

Organizations can leverage the data-driven framework proposed by (Tirkolaee et al., 2021) to enhance supply chain risk prediction. The framework involves effective synergies between a team of experts of data-driven AI and a team of experts of risk management within a supply chain. By adopting this approach, organizations can improve their ability to identify and mitigate risks, increase supply chain robustness and resilience, reduce vulnerability, and ensure continuity and profitability.

In a systematic investigation of the integration of machine learning into supply chain risk management, Schroeder and Lodemann (2021) examine various ML techniques and their applications in different SCRM stages. The authors identify that ML can be employed in risk identification, risk assessment, risk mitigation, and risk monitoring. By using ML algorithms, organizations can analyze large and complex datasets to detect patterns and trends, enabling them to identify potential risks and their sources more effectively (Schroeder & Lodemann, 2021).

Schroeder and Lodemann (2021) also emphasize the role of ML in risk assessment. ML techniques can help estimate the probability and impact of potential risks by analyzing historical data, allowing organizations to prioritize risks and allocate resources accordingly. In this regard, supervised ML methods such as decision trees, support vector machines, and neural networks have shown promising results in accurately assessing supply chain risks.

Risk mitigation strategies can also benefit from the integration of ML. Schroeder and Lodemann (2021) suggest that ML algorithms can identify effective risk mitigation actions by analyzing the relationships between risk factors and their impacts on supply chain performance. By examining the success of past risk mitigation efforts, ML can help organizations develop more effective strategies to minimize the adverse effects of supply chain risks.

Lastly, the authors highlight the role of ML in risk monitoring, which involves continuously tracking risk indicators to detect emerging risks and evaluate the effectiveness of implemented risk mitigation measures (Schroeder & Lodemann, 2021). ML can enable real-time risk monitoring by processing large amounts of data from various sources, such as IoT sensors and social media, helping organizations to stay informed about potential disruptions and respond accordingly.

3. Key Findings

The literature review supports the idea that the integration of machine learning algorithms into supply chain management can enhance the resilience of global value chains to future shocks. By leveraging the power of machine learning to process and analyze large volumes of data, supply chain managers can identify patterns and trends that might not be apparent through traditional forecasting methods and use this information to develop more robust contingency plans.

Studies have demonstrated the potential of machine learning algorithms, such as graph neural networks and artificial neural networks, to enhance supply chain risk prediction, increase supply chain agility and re-engineering capabilities, and provide insights into the procurement relationships between companies (Kosasih. 2021; Tirkolaee et al., 2021). Machine learning can also enable supply chain managers to accurately predict demand with time lags, perform scenario planning, and highlight situations where disruptions will result in difficulty meeting demands, enhancing supply chain visibility especially during disruptions (Wong et al., 2022).

GNNs, in particular, show promise in addressing supply chain visibility challenges, as they can model complex relationships and patterns within supply chain networks (Battaglia et al., 2018). These networks can not only predict hidden links but also help forecast potential disruptions and manage uncertainties, thereby enabling companies to identify vulnerabilities and take proactive measures to mitigate risks. However, the success of GNNs relies on access to reliable and up-to-date data, emphasizing the need for robust data collection and management systems (Battaglia et al., 2018).

Machine learning techniques, such as neural networks and support vector machines, can address complex management issues in global value chains (GVCs) and accurately forecast demand with time lags (Wong et al., 2022). Moreover, machine learning can enhance the agility and re-engineering capabilities of GVCs, helping businesses respond effectively to disruptions and maintain continuity of operations. One application of machine learning includes inventory control smart systems that use ML algorithms to predict future demands accurately, thus

reducing stockouts and overstock situations and ensuring cost savings and improved customer satisfaction (Benhamida et al., 2021).

However, the successful integration of machine learning into supply chain management requires careful consideration of the challenges and the development of the necessary capabilities and infrastructure. The complexity of the technology, the need for data privacy and security, and the organizational and cultural barriers to adoption may hinder the successful integration of machine learning into supply chain management. Thus, supply chain managers must adopt a proactive, risk-taking, and innovative mindset to fully exploit the potential of machine learning, and invest in the necessary data infrastructure and organizational capabilities in data analysis and interpretation.

Challenges are more pronounced for SMEs that lack the knowledge and resources to leverage technology (Wong et al., 2022). Managers must be willing to embrace digital transformation and invest in the technological infrastructure to fully realize the potential of machine learning.

The potential of machine learning to enhance supply chain visibility, resilience, and sustainability, as hypothesized, is supported by the literature review. Future research could explore a broader base of respondents and consider other factors influencing technological adoption, such as culture, management commitment, and technological readiness. Furthermore, research may also consider the moderating effects of disruptions and performance outcomes in the research, as well as policy and governance aspects to help organizations decide on the adoption of responsible machine learning algorithms.

In addition, future research could examine the integration of machine learning into SCRM stages, such as risk identification, risk assessment, risk mitigation, and risk monitoring (Schroeder & Lodemann, 2021). By investigating the effectiveness of ML algorithms in these areas, organizations can better understand how to incorporate machine learning into their SCRM processes and enhance overall resilience. Additionally, research could investigate the impact of machine learning on specific industries and sectors, as the potential benefits and challenges of integrating machine learning into supply chains may vary across different contexts (Dubey et al., 2021).

Another area for future research is the exploration of the ethical and social implications of machine learning adoption in supply chain management. This includes examining the impact of automation on employment and the need for a skilled workforce capable of working alongside machine learning systems. Researchers should also investigate potential biases in the data and algorithms used, as well as the broader consequences of increased reliance on technology in supply chain operations.

Lastly, collaboration between academia, industry, and policymakers is crucial for addressing the challenges associated with machine learning adoption and promoting responsible, sustainable, and inclusive innovation in supply chain management. Future research should identify best practices for fostering such collaborations and overcoming the barriers to machine learning integration.

4. Discussion

The literature review highlights the usefulness of using machine learning algorithms in supply chain management. These algorithms can assist in managing risks, enhancing visibility, and increasing resilience. Nevertheless, the integration of machine learning into supply chain management has several challenges that were discussed in the key findings section.

Critically analyzing the COVID-19 pandemic and the Suez Canal incident in relation to the role of machine learning in managing external shocks, it is evident that these disruptions exposed vulnerabilities in global supply chains. The COVID-19 pandemic highlighted the importance of supply chain visibility and the ability to quickly adapt to changes in demand patterns and production capacity (Ivanov, 2020). In this context, machine learning can help businesses better predict and react to shifts in demand and supply, enabling them to make more informed decisions about inventory management, production planning, and resource allocation.

During the COVID-19 pandemic, machine learning was employed to optimize distribution networks and adjust production schedules in response to rapid changes in consumer demand (Sivasubramanian, 2020). Machine learning algorithms were also used to analyze the effects of government policies and lockdown measures on supply chain performance, allowing businesses to identify potential risks and mitigate the impact of disruptions (Golan et al., 2021). By leveraging machine learning to monitor and forecast the spread of the virus, companies were able to proactively adjust their supply chain strategies, prioritize critical resources, and build more resilient and responsive operations (Sivasubramanian, 2020; Golan et al., 2021).

Similarly, the Suez Canal incident demonstrated the need for increased agility in supply chain operations. Machine learning algorithms can provide real-time insights into potential bottlenecks and alternative routing options, allowing businesses to proactively adapt their logistics strategies and minimize the impact of disruptions. Furthermore, machine learning can help identify patterns in historical data that may indicate increased vulnerability to disruptions, allowing businesses to develop contingency plans and prioritize investments in supply chain resilience (Kosasih, 2021).

In the aftermath of the Suez Canal blockage, machine learning tools could have been utilized to assess the impact of the disruption on global trade, identify affected supply chains, and estimate the cost of delays and rerouting. By integrating machine learning algorithms into supply chain management systems, businesses can build a more comprehensive understanding of their operations, allowing them to make more informed decisions in the face of uncertainty and external shocks like the Suez Canal incident.

To provide more specific recommendations for businesses to adopt machine learning in supply chain management, organizations should invest in data infrastructure and analytical capabilities, as well as fostering a culture of innovation and risk-taking (Tirkolaee et al., 2021). Developing partnerships with technology providers and collaborating with other organizations in the supply chain can also help businesses navigate the complexities of machine learning adoption and ensure successful integration (Dubey et al., 2021).

Critically discussing the implications of machine learning on job displacement and workforce re-skilling, it is important to acknowledge that the adoption of machine learning technologies may lead to the automation of certain tasks, potentially displacing workers in some roles (Dwivedi et al., 2021). However, the integration of machine learning can also create new opportunities for workforce development and upskilling. As businesses increasingly rely on data-driven decision-making, there will be a growing demand for employees with skills in data analysis, interpretation, and the management of machine learning systems (Dwivedi et al., 2021). Organizations should invest in re-skilling and training programs to ensure that their workforce can effectively collaborate with machine learning technologies and contribute to the successful implementation of these systems in supply chain management.

Addressing the barriers and challenges of incorporating machine learning into supply chain management, particularly for SMEs, it is crucial to recognize that while larger organizations may have the resources and capabilities to implement machine learning into their supply chain management, SMEs face various constraints, particularly during disruptions such as the COVID-19 pandemic. To support SMEs in overcoming these challenges, governments and industry associations can play a crucial role in providing access to resources, knowledge, and training on machine learning technologies (Hansen and Bøgh, 2020). Encouraging collaboration between SMEs and larger organizations, as well as fostering innovation ecosystems that include technology providers, academia, and policymakers, can help accelerate the adoption of machine learning in supply chain management and ensure that all businesses can benefit from the increased visibility, resilience, and sustainability that these technologies offer.

In light of the COVID-19 pandemic and the Suez Canal incident, businesses should consider the following recommendations to effectively adopt machine learning in their supply chain management:

1. Identify key areas within the supply chain where machine learning can provide the most significant impact, such as demand forecasting, inventory management, and risk assessment.
2. Establish cross-functional teams to facilitate collaboration and knowledge sharing between supply chain professionals, data scientists, and machine learning experts.
3. Implement a phased approach to machine learning adoption, starting with pilot projects to test the feasibility of new technologies and gradually scaling up successful initiatives.
4. Invest in training and development programs to equip employees with the skills necessary to work with machine learning technologies and facilitate the transition to data-driven decision-making.
5. Monitor and evaluate the performance of machine learning algorithms to ensure their continued effectiveness in addressing supply chain challenges and adapt to changing market conditions.

By following these recommendations, businesses can successfully integrate machine learning into their supply chain management processes and capitalize on the benefits of increased visibility, agility, and resilience in the face of external shocks like the COVID-19 pandemic and the Suez Canal incident.

5. Conclusion

In conclusion, integrating machine learning algorithms into supply chain management has tremendous potential to improve the resilience, visibility, and sustainability of global value chains in the face of external shocks like the COVID-19 pandemic and the Suez Canal incident. The literature review highlighted the benefits of machine learning in enhancing risk prediction, agility, re-engineering capabilities, and procurement relationships. Additionally, it can enable accurate demand prediction, scenario planning, and improved visibility during disruptions, which is essential for businesses to adapt and maintain their operations in an increasingly uncertain world.

However, the successful integration of machine learning into supply chain management requires careful consideration of challenges such as technology complexity, data privacy and security, and cultural barriers. Supply chain managers must adopt a proactive, innovative mindset and invest in the necessary data infrastructure and organizational capabilities in data analysis and interpretation to fully exploit machine learning's potential. This is particularly important for SMEs, which may face additional constraints in adopting and implementing these technologies. Governments, industry associations, and larger organizations can play a crucial role in supporting SMEs by providing access to resources, knowledge, and training, as well as fostering collaborative innovation ecosystems.

Analysis of the COVID-19 pandemic and the Suez Canal incident, demonstrated the value of machine learning in managing supply chain disruptions for businesses on how. Key recommendations to effectively adopt these technologies include identifying the most impactful areas within the supply chain, establishing cross-functional teams, implementing a phased approach to adoption, investing in employee training and development, and monitoring the performance of machine learning algorithms.

Moreover, the implications of machine learning on job displacement and workforce re-skilling, emphasizing the importance of preparing the workforce for the transition towards a more data-driven and automated supply chain management environment. By investing in training programs and fostering a culture of continuous learning, businesses can ensure that their employees have the necessary skills to work with machine learning technologies and contribute to the organization's success in an increasingly competitive global market.

Future research could broaden the respondent base, consider other factors influencing the adoption of machine learning technologies such as culture and management commitment, and examine the moderating effects of disruptions on supply chain performance outcomes. Additionally, research should also investigate the policy and governance aspects related to the responsible adoption of machine learning algorithms, ensuring that businesses can harness the power of these technologies without compromising on ethical and sustainability considerations.

Ultimately, the integration of machine learning into supply chain management can significantly enhance global value chain resilience and better prepare organizations to navigate external shocks. By acknowledging and addressing the challenges associated with the adoption of these

technologies, businesses can capitalize on the benefits offered by machine learning and maintain their competitive edge in an ever-evolving global market.

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