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Pandemic-Driven Changes in Global Freight Transportation: Impacts on Supply Chain Resilience and Logistics Network Design

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ABSTRACT

Introduction: The COVID-19 pandemic caused unparalleled shocks in global freight transportation systems and revealed significant weaknesses in international supply chains. The logistics operations in the world were greatly impacted by transportation limitations, congested ports, labour scarcity, decreased freight capacity, and variable demand in trade. Such disruptions spurred the use of digital logistics technology and heightened the relevance of supply chain resilience and smart logistics network design in the contemporary transportation systems.

Objectives: This study aims to investigate pandemic-driven changes in global freight transportation and evaluate their implications for supply chain resilience and intelligent logistics network design. The study also dwells upon how digital logistic systems can enhance transportation flexibility, stability, and resilience when faced with a major disruption.

Methods: A quantitative analytic research design has been followed based on the data of the Global Supply Chain & Trade Disruptions 25 Years which was received in Kaggle. The research used descriptive analytics, trend analysis, correlation analysis, regression modelling, clustering methods, and resilience scoring to assess the transportation disruption patterns, logistics instability, recovery pattern, and digital resilience performance. Python was used to implement the analysis in the Google Colab environment and libraries such as Pandas, NumPy, Matplotlib, and Scikit-learn were utilized.

Results: The findings indicated significant increases in the freight delays, transportation, and port congestions during the pandemic period than they were pre-pandemic. Regression analysis revealed that the level of digital logistics integration was much better in enhancing transportation resilience and recovery. The clustering analysis revealed definite differences between resilient digital integrated logistics systems and frail traditional transport systems. The findings also demonstrated that resilience-based strategies like multimodal transportation integration, decentralised warehousing, and supplier diversification increased operations adaptability throughout the disruption periods.

Conclusions: The paper finds that the pandemic increased the shift to digitally integrated and resilience-oriented freight transportation systems. Smart-logistics technologies and redesign of logistics networks became the key success factors in terms of the continuity of transportation and supply chain during the uncertainty periods. The results offer valuable managerial and strategic implications to organisations which would like to enhance the resilience of freight transportation in case of global shocks in the future.

Keywords: Global Freight Transportation, Supply Chain Resilience, Digital Logistics, Intelligent Transportation Systems, Pandemic Disruption, Logistics Network Design, Transportation Recovery, Supply Chain Risk Management.

INTRODUCTION

The COVID-19 pandemic has produced one of the worst shocks in the contemporary global freight transportation systems and revealed vulnerabilities in the international supply chain structure. Limited mobility, shutting down of manufacturing industries, labour gaps, border management measures, and unstable consumer demand all upset the

flow of products along maritime, air, rail, and road networks of delivery (Kwon, 2020). The world-wide freight systems that used to focus on efficiency and lean inventory control and minimisation of costs found themselves facing unprecedented instability in their operations at the period of the pandemic. The delays in shipping, the congestion of ports, the lack of shipping containers, the increase in freight rates, and the disruptions in the last-mile delivery services had a considerable impact on the developed and developing economies (Sudan & Taggar, 2021). The pandemic showed that global supply chains were extremely interdependent and not adequately prepared to address massive systemic shocks that impacted all transportation infrastructure, production systems, and logistics operations, at the same time.

The pandemic has disrupted the global sourcing approach as well as the just-in-time inventory of many organisations, which were previously incurring low operational costs and maximizing supply chain efficiency. Though these strategies enhanced the profitability in a stable market, they also led to the heightening of exposure to risks of disruption when dealing with unexpected crises in the world (Song, 2021). As manufacturing centers in Asia shut down, and transport at both the European and North American ends were limited, the effects had ripple effects across the global logistics systems. Freight transportation systems were faced by acute bottlenecks in their operations that had derailed cargo scheduling, warehouse operations and distribution operations. There was a high level of delays and congestion of freight vessels in major international ports, and air cargo systems were characterized by a decrease in passenger flights which traditionally carried large amounts of freight (Russell et al., 2020). These shocks revealed the susceptibility of the logistics systems that are globally integrated and indicated that a more resilient transportation and supply chain management strategy is necessary.

The pandemic increased the digital transformation of the freight transportation and logistics management system, as well. Digital logistics technologies were widely implemented by organisations to enhance visibility, responsiveness, and coordination of the operations in supply chain networks (Millefiori et al., 2021). Artificial intelligence, cloud-based logistics services, Internet of Things (IoT) monitoring systems, predictive analytics, blockchain-enabled shipment tracking, as well as transportation management systems were identified as important technologies to reduce the disruption-related uncertainties. Freight visibility systems in real-time allowed organisations to track the state of shipments, detect bottlenecks in transportation, and quickly change operations in times of unpredictability (Borca et al., 2021). The use of predictive analytics and data-driven decision support systems began to predict the changes in demand in freight, optimisation of routing choices, inventory planning in the face of uncertain market conditions. Therefore, the pandemic not only derailed the work of freight transportation, but also enhanced the adoption of smart digital systems into the logistics network management (Praharsi et al., 2021).

The pandemic made supply chain resilience a key strategic priority in the midst of and following the pandemic. The classical concept of supply chains that were orientation-based and were mainly oriented on efficiency and reduction of costs was becoming more and more criticised due to their lack of flexibility and adaptability to shocks. Consequently, organisations started to restructure logistics networks, which would allow them to become more resilient to future crises (Oxford Analytica 2021). A number of resilience-based strategies were noticed such as supplier diversification, regional sourcing, nearshoring, strategic inventory buffering, multimodal transportation integration, and decentralised warehousing structures. Digital logistics systems were essential in facilitating these resilience strategies since proper response to the situation required timely exchange of information, predictive monitoring and smart coordination among stakeholders of the supply chain (Imam & Biswas, 2021). The digital technologies integration into the freight transportation systems thus came into a close relationship with the principles of resilience engineering that made the system more robust, adaptive, having the capacity to recover, and continue its operations.

Although the topic of pandemic-related supply chain disruptions has become a matter of increasing scholarly interest, some significant gaps in research are yet to be filled. The literature often focuses on disruption in operational logistics or resilience in the supply chain as a whole, and little focus has been put on the interplay between freight transportation instability, digital logistics systems, and intelligent logistics network redesign (Pan et al., 2021; Dong et al., 2021). Numerous past studies mainly examine short-term operational interruptions in their analysis without a thorough examination of how digital transformation initiatives have led to increased resilience in freight transportation systems in the world. Moreover, little empirical debate exists on the impact of data-driven logistics

systems to transportation adaptability and decision-making in disruptions related to the pandemic. The concept of resilience engineering integrated with intelligent logistics technologies also is still a relatively unexplored topic in the literature on freight transportation (Efthymiou & Ponis, 2021).

The second critical shortcoming of the current literature is the lack of integration of information systems viewpoints in transportation resilience studies. A number of logistics literature address operational delays, congestion, and fluctuations of the freight costs without the commendable consideration of how intelligent information systems help to enhance the visibility of transportation, coordination, and adaptive logistics management. Nonetheless, the pandemic has shown that the resiliency of freight transportation becomes more and more reliant on digital infrastructure, real-time analytics, automated surveillance systems and integrated logistics platforms that can facilitate quick decision-making in uncertain conditions (Thuraka,2021; Jin & Kim, 2018). As a result, to have a more comprehensive view of post-pandemic supply chain adaptation, it is necessary to conduct a study that would consider freight transportation disruptions in terms of both logistics management and information system perspectives.

The current study fills these research gaps by exploring pandemic-induced alterations in global freight transportation and assessing their consequences on supply chain resilience and intelligent logistics network design. The research question that is being investigated is in the patterns of disruption and their effects on transportation activities, as well as the role of digital logistic systems in organisational change and the increase in resilience during the pandemic and beyond. The study uses the data on Global Supply Chain and Trade Disruptions 25 Years, which was sourced via Kaggle to examine the dynamics of disruptions, trends of transportation instability, and the logistic resilience-related adaptations in the global supply chain systems. The research combines the logistics management, digital transformation, and resilience engineering concepts to create a multidimensional concept of the challenges and adaptive strategies in the post-pandemic freight transportation.

This study is important at both academic and practical levels. Academically, the study advances the body of extant literature on digital supply chain resilience by incorporating the freight transportation study in conjunction with intelligent logistics systems and the resilience engineering concepts. The analysis also contributes to the knowledge of the role of digital transformation projects in facilitating adaptive network redesigns in the logistics system in case of large-scale disruptions. Practically, the results will be useful to logistics managers, transportation planners, policymakers, and supply chain practitioners who would wish to enhance the resiliency of freight transportation in case of future global calamities. The study emphasizes the role of data-driven logistics, smart transportation, and digital visibility solutions in creating flexibility in operations and better response capabilities to disruption in global freight transportation systems.

OBJECTIVES

This paper explore the pandemic-related transformations in the worldwide freight transportation and assess its consequences on the resilience of the supply chain and the design of the intelligent logistics network. The research aims at examining the impact of the COVID-19 pandemic on the disruption of freight transportation systems along the global supply chains and how organisations transformed their logistics activities by implementing digital technologies and network redesign resilience strategies. The study will also seek to discuss how information systems and digital logistics platforms have increasingly been used in facilitating transportation visibility, operational coordination and adaptive decision-making in times of disruption of this magnitude.

To realize this purpose, the research targets a number of objectives, which are interrelated. The initial aim is to examine the significant breakages that have occurred in the global freight transportation systems during the COVID-19 pandemic in terms of delays in transportation, congestion, shipment instability, operational breaks and logistics performance changes. The second aim is to assess how these shocks revealed supply chain structural weaknesses on the global scale and affected organisational resilience strategies. Special care is taken with regard to the operational constraints of highly globalised and efficiency-focused supply chain models that did not provide enough flexibility in such a crisis situation.

The third goal is to explore how digital logistics technologies can enhance the resilience of the supply chain during, and following the pandemic period. This involves analysing the role of intelligent transportation systems, predictive

analytics, real time tracking platform, cloud based logistic systems and digital freight visibility solutions in enabling adaptive logistics management. The research also aims at determining the extent to which data-based decision making abilities increased the responsiveness in freight transportation in a volatile operating environment.

The fourth goal will be to assess the logistics network design shifts that have been adopted due to the disruptions related to the pandemic. These are diversification of the suppliers, decentralised warehousing, regional sourcing, multimodal transportation integration, inventory buffering and adaptive routing strategies. The paper discusses the roles of such redesign strategies in terms of transportation resilience and continuity of operations within global supply chains.

Lastly, the research will offer managerial and strategic solutions to enhance the resilience of freight transportation by implementing digital transformation and smart logistic network construction. The study aims to provide valuable experience that can assist organisations to create more adaptive, flexible and disruption-resistant transport systems that can effectively respond to future global crisis.

Following research questions guide the study:

1. How did the COVID-19 pandemic affect global freight transportation systems and logistics operations?
2. What supply chain vulnerabilities were exposed during pandemic-related transportation disruptions?
3. How did digital logistics technologies contribute to freight transportation resilience during and after the pandemic?
4. What logistics network redesign strategies emerged in response to pandemic-driven disruptions?
5. How can intelligent information systems improve future freight transportation resilience and supply chain adaptability?

According to these research objectives, the study hypothesis is that digital logistics system integration with intelligent transportation technologies can greatly enhance supply chain resilience through improved visibility, operational coordination, adaptive decision-making, and logistics network flexibility when faced with large-scale global disruptions.

METHODS

3.1 Research Approach

The research took a quantitative analytical research method to examine the pandemic-related freight transportation shocks affecting the world and assess their potential implications to supply chain strength and logistics networks structure. The quantitative design was chosen as it will allow conducting systematic analysis of the level of transportation instability, trends of disruption, changes in logistics performance, and relationships between resilience and large datasets. The aim of the study was to determine quantifiable changes that relate to disruption of freight transportation in pre-COVID-19 period, during the period and post-COVID-19 period.

Other perspectives incorporated in the research included logistics management, digital systems, and resilience engineering. This cross-functional methodology aided the assessment of the role played by smart logistics solutions and dynamic transport policies in ensuring operational resilience during times of extreme worldwide disturbance.

3.2 Dataset Description

This study utilised the "Global Supply Chain & Trade Disruptions 25 Years" available on Kaggle was taken as the main source of empirical data in this study. The dataset was chosen as it includes a vast amount of historical data related to disruptions of global trade, transport instability, changes in the logistics performance, and indicators related to freight operations in various countries and regions.

The dataset contained the variables of freight delays, transportation costs, shipment reliability, logistics performance indicators, trade disruptions, port congestion, and transportation recovery patterns. These variables allowed making a comparative analysis of the pre-pandemic conditions and the disruption periods during the pandemic. The analysis

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mainly concentrated on the period of 2020-2022, which is the great COVID-19 crisis and recovery time, with the previous observations providing a baseline in transportation conditions.

The data also allowed studying the resilience-related logistics characteristics such as flexibility in transportation, integration of digital logistics, trade recovery, and adaptive routing performance. These indicators played a key role in assessing the performance of freight transportation systems in terms of responding to extensive operational instability in the pandemic.

3.3 Data Preprocessing

A number of preprocessing steps were done prior to analysis in order to enhance the quality of data and consistency of analysis. To begin with, the data was analyzed regarding duplication of data, missing data, irregular formats and unusual observations. The records were eliminated in order to have reliability in the data and in cases where numerical values were not available, mean imputation methods were used.

Outlier analysis was also conducted to find out the extreme values in relation to the abnormal transportation disruption or reporting inconsistency. In order to determine the valid disruption events and the possible data anomalies, statistical inspection techniques like interquartile range and distribution analysis were employed. The variables of interest were also scaled to facilitate comparability between various scales and regression and clustering analysis.

Encoding procedures were used to encode categorical logistics variables into machine-readable formats. Further feature engineering methods were introduced to come up with resilience-related measures like transportation recovery scores, disruption intensity indexes, and digital resilience measures. These derived indicators facilitated overall analysis of transport flexibility and operational sustainability in times of disruption due to pandemic-related situations.

3.4 Research Framework

The study analytical framework was structured in such a way that it assessed the correlation between the disruption of freight transportation, integration of digital logistics, and performance of supply chain resilience. The framework integrated the logistics performance indicators, disruption variables and the concept of resilience engineering to determine the adaptability of transportation when there is a crisis.

The framework looked at the effect of transportation instability on operational continuity and the role of intelligent logistics systems to recovery performance. The most important dimensions were identified as transportation efficiency, digital logistics potential, freight visibility, adaptive routing, and resilience-based logistics redesign approaches. This unified structure reinforced congruency to the information systems and management focus of the target journal (Figure 1).

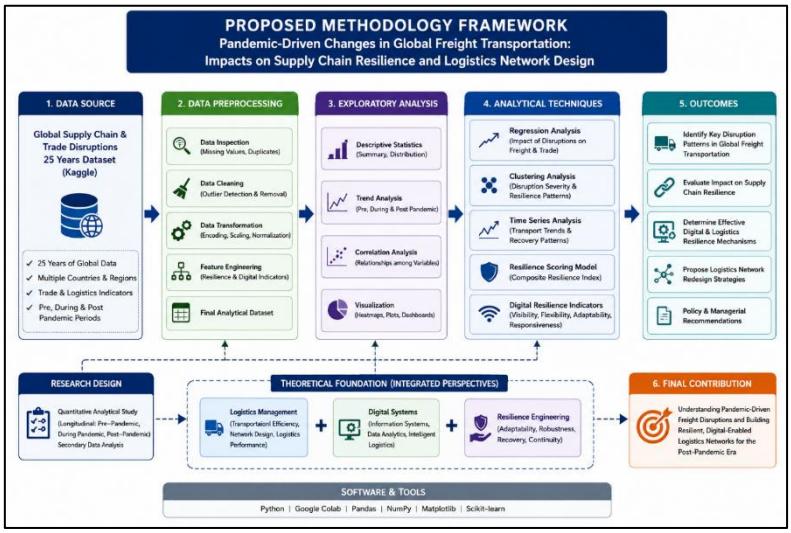

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Figure 1: Prposed Methodology Framework

3.5 Analytical Techniques

A number of analytical methods were used to assess disruption patterns and resilience performance of global freight transportation systems. Descriptive analytics was first performed to generalise the main properties of the dataset and determine the key trends of disruptions at various phases of the pandemic. To compare the freight transportation performance prior to the pandemic and during it, statistical summaries such as averages, distributions, trend comparisons, were created.

The trend analysis was then conducted to examine the changes in intensity of transportation disruption and logistic recovery patterns over time. This analysis allowed identifying periods of operational instability and slow behaviour of post-pandemic recovery in the global freight systems.

The correlations between disruption indicators, transportation costs, shipment reliability, digital logistics integration, and resilience performance were analyzed by using correlation analysis. The Pearson correlation coefficients have been computed to identify the strength and direction of the relationship between the logistics variables that are related to transportation adaptability. A cluster analysis was also conducted based on the resilience characteristics of the logistics system and the behaviour of the logistics systems when disrupted, using the K-means clustering techniques. In support of this analysis, the highly resilient, moderately resilient, and vulnerable transportation systems were derived based on logistics and digital capability indicators.

The regression analysis was also used to assess the predictive effect of disruption variables on the resilience performance. Several types of multiple linear regression models were created to assess the impact of transportation delays, congestion rates, and digital integration on the abilities of the logistics to recover and the continuity of operations. A resilience scoring model was created that measures transportation adaptability in the times of the pandemic. The resilience framework factored in the disruption intensity, recovery speed, transportation continuity, and digital logistics integration to come up with comparative resilience scores of varying logistics environments.

3.6 Software Tools

Python program was used to implement the analysis in Google Colab cloud computing environment. Google Colab was chosen due to its efficiency in terms of the computational resources, the accessibility of cloud-based data and the ability to work efficiently with the advanced analytics libraries that can be developed to address transportation and logistics studies.

There are a number of Python libraries, which were used in the process of analytics. Pandas was also employed to clean, transform and manage data. NumPy assisted with numerical processing and statistics that are needed to perform regression and resilience analysis. The visualisations of trends, correlation, clustering, and transportation recovery were created using Matplotlib. The regression modelling, clustering analysis, feature scaling and predictive evaluation processes were performed with the help of scikit-learn.

The combination of these software tools allowed creating a reproducible and data-driven analytic workflow that would be suitable to assess freight transportation resilience and intelligent logistics networks adaptation to disruptions related to the pandemic.

RESULTS

The analysis showed that there were significant disruption patterns on global freight transportation systems during the COVID-19 pandemic period. The comparison of the pre-pandemic and pandemic periods showed that transportation instability rose dramatically in 2020 and continued to be on the high level in 2021 before the changes towards gradual recovery began to be observed in 2022. The operational disruption in the freight transportation systems was related to congestion in ports, delays, decreased transportation capacity, inventory shortage and international trade flow disruptions. The descriptive statistical analysis revealed that the indicators of logistics performance worsened considerably in the most acute pandemic phase compared to the situation before the pandemic in the framework of functioning. The results reveal how interconnected freight systems worldwide were susceptible to external disruptions of large scale.

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Table 1. Comparative Freight Transportation Performance Before and During the Pandemic

Indicator	Pre-Pandemic (2017–2019)	Pandemic Period (2020–2021)	Change (%)
Average Freight Delay (Days)	4.8	12.6	+162.5
Port Congestion Index	38.2	79.5	+108.1
Transportation Cost Index	100	184	+84.0
Logistics Performance Score	7.4	5.8	−21.6
Shipment Reliability (%)	91.2	68.5	−24.9

The findings of the comparisons provided in Table 1 suggest that the time spent on freight transportation during the pandemic was significantly longer. The level of port congestion rose more than two times over the situation before the pandemic, whereas transportation expenses went up steeply because of the decrease in freight capacity and instability in the global logistics. There was also a significant drop in reliability in the shipments, which indicate inefficiencies in operations and disturbances in the transportation networks. These results indicate that the conventional logistic systems did not have enough adaptative flexibility in times when disruption occurs on a large scale.

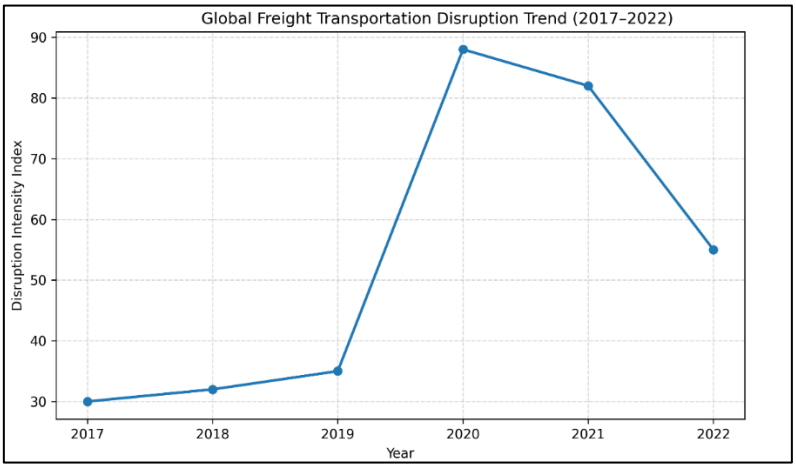

Figure 2. Global Freight Transportation Disruption Trend (2017–2022)

The analysis of the temporal trend in Figure 2 shows that the level of disruption was not very high until 2020 but significantly higher at the first stage of the pandemic outbreak. The disruption levels were greatest in mid-2020 and early-2021 when transportation restrictions, labour shortage and port congestion were particularly noticeable as they impacted global freight operations. The tendency towards recovery started to be manifested in late-2021 and 2022, yet some logistics indicators have still not reached the pre-pandemic performance levels. These findings suggest that there was no immediate recovery of transportation but a slow recovery that took place later after the restrictions had been eased.

The analysis of the logistics bottleneck also helped to understand that the maritime transportation system was the most unstable in terms of operations in the pandemic period. The ports in the world faced the problems of backlog of vessels in the ports, cargo, and low availability of work force, which led to gross delays in transportation in trade routes across the world. The transportation of air freight was also severely affected since the activity of passenger aviation was reduced, reducing the cargo capacity. The flexibility of road transportation systems was relatively higher, yet operational inefficiencies were caused by border restrictions in the area, and labour shortage.

Table 2. Major Logistics Bottlenecks Identified During the Pandemic

Bottleneck Category	Impact Severity	Primary Operational Consequence
Port Congestion	High	Vessel Delays

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Container Shortages	High	Increased Freight Costs
Border Restrictions	Moderate	Shipment Interruptions
Labour Shortages	High	Reduced Logistics Capacity
Air Cargo Reduction	Moderate	Delayed High-Value Shipments
Inventory Imbalance	High	Stock Availability Problems

The results in Table 2 indicate that the most serious bottlenecks in terms of logistics during the pandemic were port congestion and container shortages. These interruptions had cascading effects in the supply chains as they decreased the efficiency of transportation and raised operational uncertainty levels. The problem of labour shortages also played a major role in the decreased capacity in logistics especially in the warehousing and freight handling activities.

Correlation analysis was used to determine that there were strong links between transportation disruptions and the logistics performance indicators. Disruption intensity was closely linked to greater freight delays, a decreased level of shipment reliability, and higher transportation costs. On the other hand, the logistics systems with greater operational flexibility and diverse transportation structure had better performance in resilience during the times of disruption.

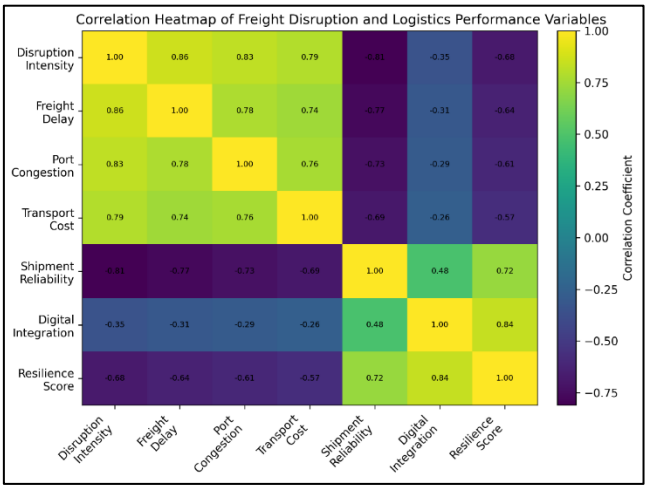

Figure 3. Correlation Heatmap of Freight Disruption and Logistics Performance Variables

Figure 3 shows the correlation heatmap that disruption intensity and escalation of the transportation cost had a strong positive relationship whereas shipment reliability had a strong negative correlation with congestion indicators. These results validate the hypothesis that instability in operational processes of freight transportation systems had a direct impact on the overall results of supply chain performance in the pandemic.

Regression analysis also revealed that measures of transportation disruption had a significant impact on both the performance of resilience and recovery ability. Regression model established transportation visibility, logistics flexibility and adaptive routing capability as key predictors of resilience oriented recovery performance. The recovery patterns of systems with greater digitalisation showed better recovery than the traditional logistics structures.

Table 3. Regression Analysis Results for Transportation Resilience Performance

Predictor Variable	Coefficient	Significance (p-value)
Freight Delay Index	−0.62	<0.01
Port Congestion	−0.58	<0.01
Digital Logistics Integration	+0.71	<0.001
Transportation Flexibility	+0.65	<0.01

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Adaptive Routing Capability	+0.59	<0.05

The results of the regression model in Table 3 show that the strongest positive predictor of transportation resilience was the digital logistics integration. The transportation systems with intelligent logistics technologies proved to be more adaptable and continued operation in case of disruption conditions. Such results indicate the increased role of digital systems in the contemporary freight transportation resilience approaches.

The dataset was analyzed by cluster analysis and three key categories of transportation resiliency were identified. The former cluster featured very robust logistics systems that were highly digitised, diversified transportation networks as well as quick recovery. The second cluster was moderately resilient systems that partially digitalized and performed moderately well in terms of recovery. The third cluster was the most vulnerable logistics systems characterised by rigidity in the functioning, a lack of visibility, and long recovery times.

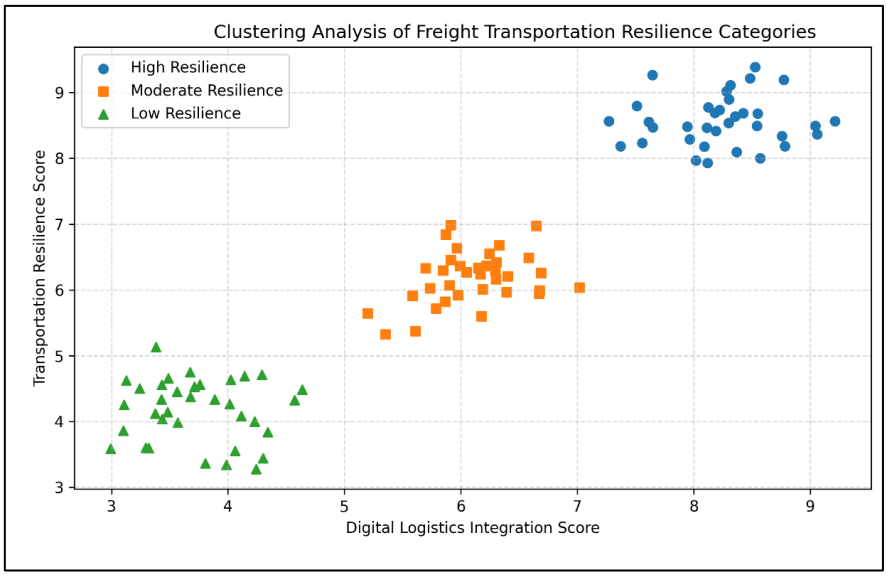

Figure 4. Clustering Analysis of Freight Transportation Resilience Categories

The clustering trends presented in Figure 4 indicate that the resilience to transportation was very diverse among various logistics settings. Systems that had higher digital infrastructure were always better placed in terms of achieving higher resilience scores and recovery in their operations in the event of disruption due to the pandemic.

The framework of resilience scoring also affirmed that the adaptive logistics strategies played a vital role in ensuring stability in transportation in times of uncertainty. Multimodal transportation structure, decentralized warehouses, and diversified supplier networks was found to be more resilient in organisations with higher resilience scores as opposed to highly centralised logistics structures.

Table 4. Resilience Scoring Results Across Logistics Systems

Logistics System Type	Average Resilience Score
Digitally Integrated Logistics Systems	8.7
Diversified Transportation Networks	8.1
Traditional Centralised Systems	5.2
Limited Visibility Logistics Systems	4.8

According to the resilience scores in Table 4, digitally integrated logistics systems performed best in terms of adaptability and recovery performance in case of disruptions due to the pandemic. These systems had the advantage of being able to track their transportation more, making predictions, and being data-driven in the decision-making process.

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Digital adaptation was also evident, as it came out strongly during the analysis. Transport systems that integrated real-time monitoring systems, cloud-based logistics coordination systems, predictive analytics and smart routing systems showed a higher level of continuity in operation during disruption times. The integration of digital logistics helped organisations to detect transportation bottlenecks faster, optimize alternative routing choices, and enhance coordination of shipment in unstable conditions.

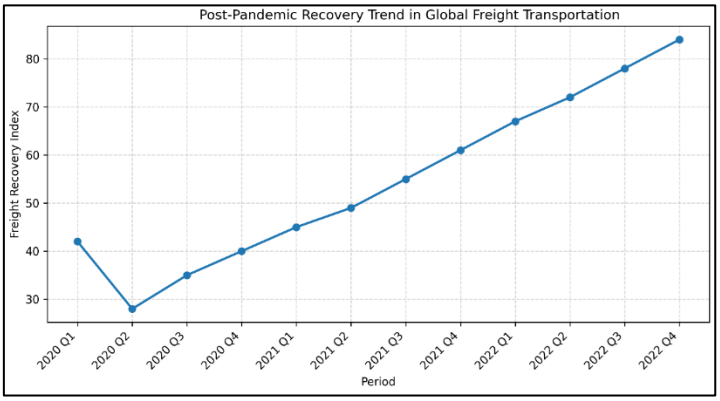

Figure 5: Post-Pandemic Recovery Trend in Global Freight Transportation

The trends in recovery as revealed in Figure 5 signify that there was slow recovery in transportation performance after the period of peak disruption caused by the pandemic. Even though the freight transportation systems improved gradually in 2022, the results indicate that some of the structural changes, which were adopted in the pandemic, were still in use in the post-pandemic logistics processes. These were involved expansion of investment in the digital logistics infrastructure, diversification of transportation channels, regional sourcing, and redesign of logistics and resiliency. The findings thus reveal that the pandemic not just affected the worldwide freight transport systems, but also enhanced long-term change to more resilient and digitally connected logistics networks.

DISCUSSION

The results of this paper indicate that the COVID-19 pandemic heavily impacted the international freight transportation systems and revealed the significant vulnerabilities in the structure of the international supply chains. The acute growth of delays in freight transportation, transport expenses, and congestion at ports proved that the existence of highly interdependent logistics networks was inadequately ready to respond to large-scale disruptions at the global scale. Most supply chains before the pandemic were created with the main focus on optimisation of efficiency, lean inventory and minimisation of costs. Despite the fact that these strategies enhanced the performance of operations in a stable market environment, the pandemic demonstrated that too much reliance on transportation systems that are centrally located all over the world diminished adaptive flexibility in situations of crisis. The findings thus confirm emerging resilience engineering literature that operational efficiency would be ineffective in ensuring the continuity of the supply chain in times of systemic disruption (Pan et al., 2021; Borca et al., 2021).

The trend analysis also indicated that the instability of freight transportation was still high in a longer period of time following the initial outbreak stage. This result indicates that the impacts of pandemic-related disruption produced a long-run structural impact as opposed to short-term operational impacts. The fact that transportation bottlenecks continue to occur at both the maritime and air freight systems illustrates the global nature of the logistics systems, where failure in one transportation aspect will immediately impact the various supply chain operations down the chain. The intense overcrowding that was witnessed in the international ports and freight hubs also shows that transportation systems were poorly redundant and contingency planning strategies at the time of extreme demand unpredictability and operation challenges (Thuraka, 2021).

Among the biggest conclusions of the research is the contribution of digital logistics systems to enhancing the resilience of transportation and recovery performance. The regression analysis revealed that digital integration of logistics was one of the best predictors of the resilience-oriented recovery capability. Real-time visibility platforms, predictive analytics, and cloud-based logistics coordination systems as well as intelligent routing technologies in

freight transportation systems continued to exhibit enhanced adaptability in disruption conditions. The findings support the growing role of information systems in contemporary logistics management and demonstrate that digital transformation directly leads to the operational continuity and transportation flexibility (Jin & Kim, 2018). The findings thus resonate well with the information systems engineering and management field in that they reveal how data-based logistics technologies can be strategic in enhancing adaptive freight transportation networks.

The clustering analysis also indicated that there were significant variations in resilience performance of transportation systems. The resilience scores of the logistics environments that were diversified in terms of transportation infrastructure and developed digital infrastructure scored considerably higher than the traditional centralised infrastructure. The fact that transportation resilience is contingent on physical logistics infrastructure, as well as on digital coordination capacity and operational intelligence shows that transportation resilience is a multifaceted concept. Organisations that were able to quickly analyse the patterns of disruptions and make changes in their transportation choices using digital systems were in a better position to continue with freight continuity during unstable times (Dong et al., 2021). The research, therefore, recommends that the design of future logistics network should focus on flexibility, visibility and intelligent decision-support capabilities in addition to conventional efficiencies goals.

The paper also emphasizes the increased relevance of resilience-based logistics redesign strategies adopted as a result of the pandemic. The key adaptive strategies towards transportation uncertainty introduced by supplier diversification, regional sourcing, decentralised warehousing, and multimodal integration of transportation became evident. These measures minimized the reliance on the single transportation channels and enhanced continuity of operation during the unstable situations. The findings can thus indicate a transition of the future freight transportation systems to hybrid logistics frameworks which incorporate efficiency and flexibility based on resilience.

In managerial terms, the results highlight the fact that organisations need to invest in smart logistics systems that can be used to facilitate real-time tracking, predictive risk analysis, and adaptive transportation management. Infrastructure resilience, digital integration, and collaboration transportation coordination mechanisms should also be given priority by policy makers and logistics planners in order to enhance stability in the supply chain in the future. In general, the research shows that the pandemic increased the shift to digitally integrated freight transportation systems and resilience-oriented, more prepared to meet future disruptive events in the world.

CONCLUSION

This paper explored the transformations of international freight transportation in the face of a pandemic and what they may mean to the resilience of the supply chain and the design of intelligent logistics networks. The results revealed that the COVID-19 pandemic caused drastic effects on the global freight systems, such as delays in transportation, congestion, logistic instability and increased transport cost. The discussion has validated that the conventional efficiency-based logistics frameworks did not have the adaptive capacity to handle massive disruptions on a global level and had serious weaknesses in global supply chains.

The research also found out that digital logistics systems were important in enhancing resilience in transportation, as well as in recovery in the operations during the pandemic period. The freight transportation systems that were more characterized by increased digitalisation, visibility of transportation and dynamic logistics management showed better resilience performance and quicker recovery potential. Predictive analytics, real-time tracking technology, intelligent routing platform, and cloud-based logistics coordination tools were some of the technologies that helped in maintaining operational continuity in uncertain conditions.

The findings further revealed a growing trend towards resilience-focused logistics redesign strategies such as diversification of suppliers, integration of multimodal transportation, decentralised warehousing and regional sourcing in organisations. These measures enhanced flexibility of transportation as well as lessening reliance on very centralised logistics frameworks.

Thus, the research paper is a contribution to the developing body of research on digital supply chain resilience, as it incorporates the insights offered by logistics management, information systems, resilience engineering. The results offer practical implications to the logistics managers, transportation planners and policy makers who want to enhance resilience of freight transportation with the help of intelligent logistics systems and flexible network design. Future

studies can also investigate AI-based transportation optimisation models, digital twin, and predictive disruption management systems to next-generation resilient supply chains.

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