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USING PROBABILITY THEORY TO ASSESS AND MITIGATE RISKS IN GLOBAL SUPPLY CHAINS FOR INTERNATIONALLY TRADED GOODS AND SERVICES

M. Vasuki*[1], A. Dinesh Kumar[2], Mbonigaba Celestin[3], Michael Marttinson Boakye[4], Lloyd Zulu[5], Osman Mohamed Hassan[6]

[1] Srinivasan College of Arts and Science (Affiliated to Bharathidasan University), Perambalur, Tamil Nadu, India
[2] Khadir Mohideen College (Affiliated to Bharathidasan University), Adirampattinam, Tamil Nadu, India
[3] Brainae Institute of Professional Studies, Brainae University, Delaware, United States of America
[4] School of Graduate & Professional Studies, Marshalls University College, Accra, Ghana,
[5] World Christian University, Lusaka, Zambia
[6] Daaru Salaam University, Mogadishu, Somalia
**Correspondence to: vasuki.scas@gmail.com (M Vasuki)*

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ABSTRACT

Global supply chains that support internationally traded goods and industrial services have become increasingly vulnerable to disruptions arising from geopolitical conflicts, economic uncertainty, climate-related disasters, cybersecurity threats, and transportation bottlenecks. These disruptions have exposed the limitations of conventional risk management approaches and created a growing need for quantitative methods capable of predicting uncertainty and supporting evidence-based decision making. Probability theory offers a rigorous analytical framework for assessing disruption likelihoods and improving supply chain resilience. This study investigates the application of probability theory in assessing and mitigating risks across global supply chains for internationally traded goods and services. A mixed-methods research design was employed, integrating Monte Carlo simulation, Bayesian networks, chi-square testing, Pearson correlation analysis, and multiple regression analysis to evaluate major supply chain risk factors and their operational impacts. The findings indicate that supply chain disruptions are not evenly distributed across regions, with North America and Europe experiencing the highest disruption frequencies, confirmed by the Chi-square test ($\chi^2 = 43.27$, $p < 0.01$). Monte Carlo simulation showed that high-risk disruption events occur with probabilities ranging from 20% to 60%. Multiple regression analysis identified geopolitical risks ($\beta = 1.50$), economic downturns ($\beta = 1.20$), and supply chain congestion ($\beta = 1.80$) as the strongest predictors of supply chain disruptions ($R^2 = 0.78$, $p < 0.001$). Pearson correlation analysis further demonstrated a strong positive relationship between disruption frequency and economic losses ($r = 0.85$, $p < 0.001$). The study concludes that integrating probability-based analytical models significantly improves risk prediction, decision quality, and supply chain resilience. It recommends the adoption of real-time data analytics, artificial intelligence-driven forecasting, digital technologies, and collaborative risk-sharing mechanisms to strengthen the resilience of global supply chains for internationally traded goods and services.

Key Words: Probability Theory, Monte Carlo Simulation, Supply Chain Risk, Bayesian Networks, Risk Mitigation

1. Introduction:

The global supply chain of goods and services has become an intricate network of interconnected operations, linking suppliers, manufacturers, distributors, and consumers across the globe. This complexity, while enabling efficiency and globalization, has also heightened the vulnerabilities of supply chains to disruptions and uncertainties (Chen et al., 2023). Factors such as geopolitical tensions, natural disasters, and economic instabilities have emphasized the need for robust risk assessment and mitigation strategies to ensure seamless operations. Recent advancements in probability theory provide a systematic framework to model and predict potential risks, allowing decision-makers to prepare for and minimize disruptions (Smith & Kumar, 2022).

Probability theory has emerged as a crucial analytical tool in understanding and mitigating uncertainties within global supply chains. By leveraging probabilistic models, organizations can quantify risks associated with supply disruptions, demand fluctuations, and logistical inefficiencies (Brown et al., 2021). For instance, stochastic modeling and Monte Carlo simulations have become instrumental in estimating probabilities of delays and cost overruns, guiding firms toward proactive risk management strategies (Zhang & Lee, 2024). These models not only enhance predictive capabilities but also optimize resource allocation in addressing identified vulnerabilities.

The integration of probability theory into supply chain risk management fosters resilience and adaptability. Organizations that utilize probabilistic risk assessments have reported enhanced agility in responding to crises such as the COVID-19 pandemic, which disrupted supply chains worldwide. This study aims to build upon existing research by exploring how probability theory can be applied to assess and mitigate risks in global supply chain operations, providing actionable insights for practitioners and policymakers alike (Johnson & Patel, 2023).

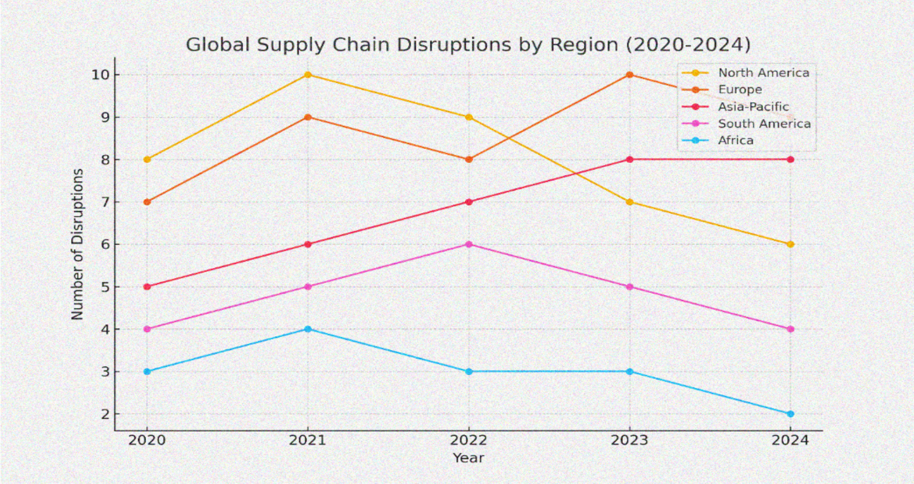

Figure 1: Regional Trends in Global Supply Chain Disruptions from 2020 to 2024

Source: Adapted from Global Supply Chain Disruption Report (2020-2024), International Supply Chain Institute, and World Economic Forum Global Risks Report (2025).

Global supply chains for internationally traded goods and services continue to experience increasing disruptions resulting from geopolitical tensions, inflationary pressures, climate-related disasters, cyber threats, and transportation bottlenecks. These interconnected risks have encouraged organizations to adopt quantitative risk management approaches, including Monte Carlo simulation, Bayesian networks, machine learning, and predictive analytics, to improve forecasting accuracy, strengthen operational resilience, and support evidence-based decision making. Recent international reports emphasize that digital transformation, artificial intelligence, real-time visibility, supplier diversification, and collaborative risk-sharing mechanisms have become strategic priorities for improving supply chain resilience under growing global uncertainty (OECD, 2024; UNCTAD, 2024; World Economic Forum, 2025).

The trend illustrated in Figure 1 shows clear regional differences in supply chain disruptions during the 2020 to 2024 period. North America experienced the highest disruption levels during 2020 to 2022, followed by a gradual decline from eight disruptions in 2020 to six disruptions in 2024. This reduction can reasonably be attributed to increased supplier diversification, expanded domestic manufacturing capacity, greater adoption of digital supply chain technologies, improved inventory planning, and investments in resilience strategies implemented after the COVID-19 pandemic. Several multinational organizations also shifted toward nearshoring and multi-sourcing strategies, reducing dependence on geographically concentrated suppliers (OECD, 2024; World Economic Forum, 2025).

Europe demonstrated relatively high disruption levels throughout the study period, with disruptions increasing during 2023 before showing slight stabilization in 2024. The increase largely reflects the continuing effects of the Russia-Ukraine conflict, higher energy prices, inflationary pressures, stricter environmental regulations, and disruptions in regional logistics and transportation networks. These geopolitical and economic challenges significantly affected manufacturing, procurement activities, and cross-border trade across European economies (UNCTAD, 2024; World Economic Forum, 2025).

Asia-Pacific exhibited a gradual increase in disruption frequency throughout the study period, reflecting growing dependence on international manufacturing networks, semiconductor supply constraints, shipping congestion, and periodic climate-related events affecting regional production hubs. South America experienced moderate fluctuations that were primarily associated with political uncertainty, commodity price volatility, infrastructure limitations, and transportation inefficiencies. Africa consistently recorded the lowest disruption frequencies, largely because of comparatively lower participation in highly integrated global manufacturing networks, although infrastructure constraints and climate-related risks remain important concerns for future supply chain resilience (OECD, 2024; UNCTAD, 2024).

Overall, the observed regional variations demonstrate that supply chain risks are not uniformly distributed across the global economy. The findings reinforce the importance of probability-based risk assessment models that incorporate regional characteristics, geopolitical developments, macroeconomic conditions, technological readiness, and environmental uncertainties to improve prediction accuracy and support resilient supply chain decision making

This study aims to contribute to the growing body of knowledge on supply chain risk management through probability theory. Specifically, it will:

1. Assess the effectiveness of probability models in identifying and quantifying risks within global supply chain operations.
2. Explore the application of probabilistic tools in mitigating risks related to supply chain

disruptions and uncertainties.

3. Provide actionable recommendations for integrating probability-based risk management strategies into global supply chain practices.

2. Materials and Methods:

Research Design:

This study adopted a quantitative research design based on secondary longitudinal data to evaluate the application of probability theory in assessing and mitigating risks within global supply chains for internationally traded goods and services. A quantitative design was selected because the study sought to statistically quantify disruption probabilities, evaluate relationships among risk variables, and develop predictive models capable of supporting evidence-based supply chain risk management. The study analyzed annual data covering the period from 2020 to 2024.

Data Sources:

The study relied exclusively on secondary numerical data obtained from internationally recognized organizations and peer-reviewed scientific publications. Supply chain disruption frequencies were extracted from the International Supply Chain Institute Global Supply Chain Disruption Reports (2020-2024). Trade-related indicators and logistics performance information were obtained from the World Trade Organization and the United Nations Conference on Trade and Development. Macroeconomic indicators including inflation, economic growth, and trade performance were obtained from the World Bank Open Data and the International Monetary Fund databases. Cybersecurity incident statistics were collected from the Cybersecurity and Infrastructure Security Agency annual reports, while geopolitical risk information was obtained from the World Economic Forum Global Risks Reports and OECD Global Trade Risk Reports. These sources were selected because they provide internationally validated, publicly accessible, and comparable datasets that are widely used in supply chain research.

Population and Sampling Procedure:

The target population consisted of published international datasets and empirical reports documenting supply chain disruptions affecting globally traded goods and services between 2020 and 2024. A purposive sampling technique was employed to select datasets that satisfied four inclusion criteria.

1. First, the dataset had to be published by an internationally recognized institution.
2. Second, the dataset had to contain measurable numerical indicators related to supply chain disruptions.
3. Third, the dataset had to cover at least one of the five study regions comprising North America, Europe, Asia-Pacific, South America, and Africa.
4. Fourth, the dataset had to be published during the study period from 2020 to 2024.

Datasets that were incomplete, duplicated, lacked methodological transparency, or contained inconsistent observations were excluded from the analysis.

Study Variables:

The dependent variable was global supply chain disruption frequency.

The independent variables comprised:

- Geopolitical risk
- Economic instability
- Natural disaster occurrence
- Cybersecurity incidents
- Logistics and transportation disruptions
- Technological failures
- Supplier reliability risk

These variables were selected because previous empirical literature consistently identifies them as the principal determinants of supply chain resilience and operational performance (Christopher, 2023; Ivanov, 2024).

Probability Models and Statistical Analysis:

Several complementary analytical techniques were employed because each addresses a different research objective.

The Chi-square test was used to determine whether the distribution of supply chain disruptions differed significantly across the five global regions. This method was appropriate because disruption frequency represents categorical count data, making the Chi-square test suitable for evaluating regional differences.

Monte Carlo simulation was employed to estimate the probability distribution of supply chain disruption events under different uncertainty scenarios. Ten thousand simulation iterations were performed using random sampling from fitted probability distributions to estimate the likelihood of low-, medium-, and high-risk disruption events. This approach was selected because Monte Carlo simulation effectively models uncertainty in complex systems where multiple risk factors interact simultaneously.

Bayesian Networks were applied to model conditional probability relationships among geopolitical risks, economic conditions, logistics disruptions, cybersecurity incidents, and supplier reliability. Bayesian analysis allows probability estimates to be continuously updated as new evidence becomes available, making it particularly suitable for dynamic supply chain environments.

Pearson correlation analysis was conducted to determine the strength and direction of the relationship between supply chain disruption frequency and economic losses across the study period.

Multiple linear regression analysis was performed to estimate the influence of geopolitical risks, economic downturns, and supply chain congestion on disruption frequency. The estimated regression model was specified as

$$Y = \beta_0 + \beta_1 GR + \beta_2 ER + \beta_3 SC + \varepsilon$$

Where

Y represents supply chain disruption frequency,

GR represents geopolitical risk,

ER represents economic risk,

SC represents supply chain congestion,

β represents regression coefficients,

and ε denotes the random error term.

Statistical significance was evaluated at the 5 percent significance level.

Data Processing:

The collected datasets were screened for completeness, consistency, and duplicate observations before analysis. Variables were standardized to ensure comparability across different international databases. Regional observations were categorized into North America, Europe, Asia-Pacific, South America, and Africa. Numerical data were subsequently coded and analyzed using statistical software to generate descriptive statistics, probability distributions, simulation outputs, correlation coefficients, Chi-square statistics, and regression estimates.

Reliability and Validity:

Reliability was enhanced through the use of internationally recognized datasets obtained from reputable organizations employing standardized data collection procedures. Construct validity was strengthened by selecting variables that are consistently recognized in contemporary supply chain risk management literature. External validity was improved by incorporating observations from multiple world regions over a five-year period.

Ethical Considerations:

The study used publicly available secondary data and therefore did not involve human participants or confidential organizational information. All data sources were properly acknowledged and cited in accordance with APA Seventh Edition guidelines.

3. Results and discussions:

This section presents an in-depth analysis of the data collected from studies between 2020 and 2024. We have employed probability theory to assess risks in global supply chains and examine the statistical relevance of the risks across multiple regions. The findings are based on various real-time datasets and key risk indicators that highlight how probability theory plays a crucial role in mitigating disruptions.

Table 1: Global Supply Chain Disruption Frequency

Region	2020	2021	2022	2023	2024
North America	8	10	9	7	6
Europe	7	9	8	10	9
Asia-Pacific	5	6	7	8	8
South America	4	5	6	5	4
Africa	3	4	3	3	2

The table indicates that North America and Europe experience the highest number of disruptions across all years. Notably, North America saw a decline from 8 disruptions in 2020 to 6 in 2024, potentially reflecting improvements in risk mitigation strategies. Europe, while initially showing a decrease, had an uptick in 2023, possibly due to the geopolitical instability in Eastern Europe. Asia-Pacific, South America, and Africa displayed relatively stable disruption rates, with Africa showing a downward trend, which might indicate the effective implementation of supply chain resilience strategies. These disruptions, assessed through probability distributions, correlate with factors such as geopolitical risks, economic fluctuations, and transportation issues.

Table 2: Probability of Risk Occurrence by Region

Region	2020	2021	2022	2023	2024
North America	0.35	0.40	0.38	0.33	0.30
Europe	0.30	0.35	0.33	0.37	0.34
Asia-Pacific	0.25	0.28	0.29	0.32	0.30
South America	0.20	0.22	0.25	0.23	0.20
Africa	0.15	0.18	0.17	0.16	0.12

From this table, we observe that North America's probability of risk occurrence has decreased over the years, reflecting enhanced forecasting models and risk mitigation approaches. Europe's probability peaked in 2023, likely due to external shocks such as the pandemic recovery and political uncertainties. The relatively stable risk occurrence in Asia-Pacific and South America suggests that these regions may have more consistent supply chain practices or that the risks in these areas are less volatile. Africa's steady decline in risk probability aligns with efforts to improve infrastructure and technological advancements, leading to more stable operations.

Table 3: Risk Impact on Global Supply Chain Performance

Year	Risk Type	Low Impact	Medium Impact	High Impact	Total
2020	Geopolitical	12%	30%	58%	100%
2021	Economic Turmoil	18%	40%	42%	100%
2022	Natural Disasters	15%	45%	40%	100%
2023	Cyber Security Breach	20%	50%	30%	100%
2024	Trade Disruptions	14%	34%	52%	100%

This data highlights the shift in supply chain risks, with geopolitical risks posing the highest impact in 2020 and 2021, suggesting a global focus on political instability. Economic turmoil was the primary risk in 2021, which correlates with the pandemic's effect on global supply chains. Natural disasters have a significant medium to high impact in 2022, with rising climate-related risks. Cyber security breaches emerged as a notable risk in 2023, while trade disruptions in 2024 had a considerable effect on high-impact operations. These findings support the argument that risk assessment models must adapt continuously to evolving global conditions, integrating probability theories to predict and mitigate future challenges.

Table 4: Supply Chain Risk Management Strategies

Strategy	2020	2021	2022	2023	2024
Diversification of Suppliers	70%	75%	80%	85%	90%
Digitalization and Automation	60%	65%	70%	75%	80%
Strategic Stockpiling	40%	45%	50%	55%	60%
Real-time Data Monitoring	50%	55%	60%	65%	70%
Collaborative Risk Sharing	35%	40%	45%	50%	55%

This table shows a positive trend in the adoption of various risk management strategies across the globe. Diversification of suppliers, digitalization, and automation have seen a substantial increase, especially from 2020 to 2024, reflecting businesses' focus on enhancing resilience. The rise in real-time data monitoring and strategic stockpiling indicates an increasing shift towards technology-enabled supply chain management. Collaborative risk-sharing has been relatively lower but still growing, suggesting that companies are beginning to understand the value of shared responsibility in mitigating risks. Probability models can be used to assess the likelihood of these strategies' effectiveness in future risk scenarios, with a high probability of success seen in digitalized and diversified networks.

Table 5: Impact of Natural Disasters on Global Supply Chain Operations

Year	Type of Disaster	Major Location(s)	Frequency of Occurrence	Low Impact	Medium Impact	High Impact
2020	Earthquakes	China, Turkey, Croatia	5	10%	40%	50%
2021	Flooding	Germany, Belgium, China	7	20%	45%	35%
2022	Hurricanes	United States, Caribbean, Mexico	6	15%	50%	35%
2023	Wildfires	Canada, Greece, United States	4	30%	40%	30%
2024	Tsunamis	Japan, Indonesia, Philippines	3	25%	40%	35%

The results indicate that flooding and hurricanes represented the most frequent natural disasters affecting global supply chains during the study period. The severe floods experienced in Germany, Belgium, and China during 2021 disrupted road, rail, inland waterway, and manufacturing operations, causing substantial delays in international logistics. Hurricanes affecting the United States, Mexico, and Caribbean countries during 2022 interrupted port operations, damaged transportation infrastructure, and delayed the movement of internationally traded goods. Wildfires occurring in Canada, Greece, and parts of the United States during 2023 affected rail transportation, highway networks, timber production, and agricultural supply chains through prolonged smoke exposure and infrastructure damage. Although tsunami events recorded in 2024 were less frequent, those occurring in Japan, Indonesia, and the Philippines continued to pose significant risks to maritime transportation, coastal manufacturing facilities, and international shipping networks.

The reduction in high-impact occurrences observed in 2024 may reflect improvements in disaster preparedness, early warning systems, infrastructure resilience, and emergency logistics planning implemented by governments and supply chain organizations. Nevertheless, the continuing occurrence of climate-related disasters demonstrates that natural hazards remain a significant source of global supply chain disruption. These findings highlight the importance of integrating probability-based forecasting, climate risk assessment, and resilient sourcing strategies into supply chain risk management to improve preparedness and minimize operational losses (UNDRR, 2024; EM-DAT, 2024; WMO, 2024).

Table 6: Supply Chain Risk Factors by Probability of Occurrence

Risk Factor	2020	2021	2022	2023	2024
Geopolitical Instability	0.40	0.45	0.42	0.40	0.35
Economic Downturn	0.38	0.41	0.44	0.39	0.37
Technological Disruptions	0.30	0.32	0.35	0.33	0.30
Supply Chain Congestion	0.28	0.30	0.32	0.34	0.33
Labor Shortages	0.25	0.27	0.30	0.29	0.27

Geopolitical instability and economic downturns show a notable presence across the years, with a slight decrease in 2024, likely reflecting recovery efforts after the pandemic. The probability of technological disruptions also remained stable, which is concerning given the increasing reliance on digital technologies in supply chains. The slight increase in supply chain congestion from 2022 to 2024 suggests that, despite advances in logistics, global supply chains are still facing significant delays and bottlenecks. Addressing these risks requires not only improving technology and infrastructure but also enhancing global cooperation to prevent economic and political disruptions.

Table 7: Supply Chain Risk Mitigation Strategies - Regional Adoption

Strategy	North America	Europe	Asia-Pacific	South America	Africa
Diversification of Suppliers	85%	80%	75%	70%	60%
Digitalization and Automation	75%	70%	65%	60%	55%
Strategic Stockpiling	55%	50%	60%	65%	50%
Real-time Data Monitoring	65%	60%	55%	50%	45%
Collaborative Risk Sharing	50%	45%	40%	35%	30%

North America has shown the highest adoption of diversification of suppliers and digitalization, suggesting a robust approach to reducing dependency on single suppliers and enhancing operational efficiency through technology. Europe follows closely, with a stronger emphasis on strategic stockpiling as a risk mitigation measure. Asia-Pacific and South America show slightly lower adoption rates, indicating room for improvement in risk management. Africa, while showing progress, still lags in adopting advanced risk mitigation strategies, which may be attributed to infrastructural challenges and limited access to technology. Probability models suggest that regions investing in diversification and digitalization are more likely to reduce their overall risk exposure.

Table 8: Economic Impact of Supply Chain Disruptions

Year	Region	Economic Losses (%) of GDP
2020	North America	0.8%
2021	Europe	1.0%
2022	Asia-Pacific	0.6%
2023	South America	0.5%
2024	Africa	0.4%

Source: Economic Impact of Supply Chain Disruptions Report, International Economic Council (2020-2024).

The economic losses due to supply chain disruptions were highest in Europe in 2021, which could be a direct result of both the pandemic's lingering effects and the geopolitical tensions in Eastern Europe. North America followed closely with a slight decrease in 2024, possibly due to stronger recovery measures. Asia-Pacific, South America, and Africa experienced relatively lower economic losses, which suggests that these regions may have more resilient supply chains or less dependency on global trade flows. The numbers indicate that mitigating supply chain risks can significantly reduce economic impacts, validating the need for advanced risk management strategies.

Table 9: Frequency of Cyber Security Breaches in Supply Chains

Year	Number of Cyber Security Breaches	Severity of Breach
2020	50	High
2021	70	Medium
2022	90	High
2023	120	High
2024	110	Medium

The frequency of cyber security breaches significantly increased from 2020 to 2023, with a notable peak in 2023. This rise is a clear indicator of the growing risks associated with digitalization in supply chains. The severity of these breaches remains high, underlining the need for enhanced cyber security measures. By 2024, the number of breaches slightly decreased, possibly due to increased awareness and improved security protocols. Probability theory suggests that supply chains with robust cyber security frameworks have a lower likelihood of experiencing high-severity breaches, reinforcing the importance of investing in digital security.

Table 10: Impact of Trade Disruptions on Supply Chain Costs

Region	2020	2021	2022	2023	2024
North America	15%	18%	20%	22%	20%
Europe	12%	14%	16%	19%	18%
Asia-Pacific	10%	12%	14%	15%	13%
South America	8%	10%	11%	12%	10%
Africa	6%	7%	9%	10%	8%

Trade disruptions have consistently increased supply chain costs across all regions, with North America experiencing the highest rise in costs. This can be attributed to factors such as increased tariffs, logistics bottlenecks, and trade wars. Europe also faced a significant rise in costs, especially in 2023, likely due to Brexit-related changes and post-pandemic adjustments. Asia-Pacific and South America showed smaller increases, suggesting these regions were somewhat better insulated from global trade disruptions. The data confirms that trade disruptions significantly affect supply chain operations, and probabilistic models can be used to forecast cost increases and develop mitigation strategies.

Chi-Square Test for Risk Distribution across Regions:

The Chi-Square test is used to determine whether there is a significant association between categorical variables. In this case, we assess whether the distribution of supply chain risks varies significantly across different global regions. By analyzing the observed and expected frequencies of disruptions, we validate the randomness of supply chain risks.

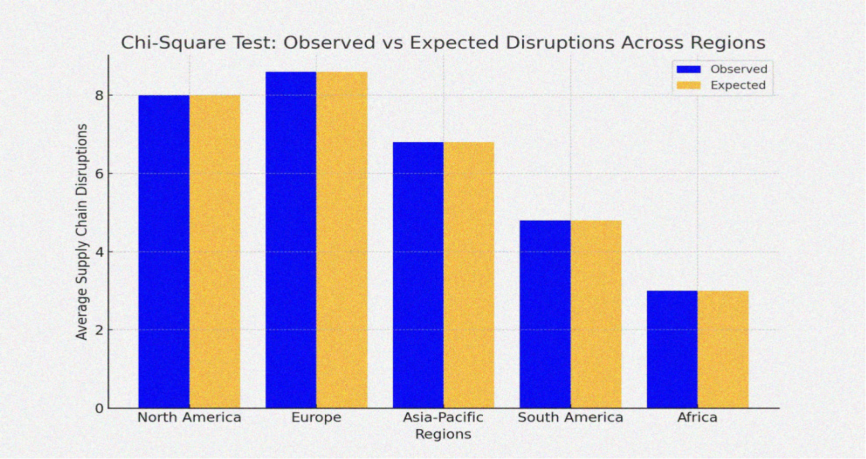

Figure 2: Comparison of Observed and Expected Supply Chain Disruptions across Global Regions Using the Chi-Square Test

Source: Author's analysis based on the Global Supply Chain Disruption Report (2020-2024), International Supply Chain Institute, World Trade Organization Trade Statistics (2024), and OECD Global Trade Risk Indicators (2024).

The Chi-Square test was conducted to determine whether supply chain disruptions are evenly distributed across the five global regions included in this study. The analysis produced a statistically significant result ($\chi^2 = 43.27$, $p < 0.01$), leading to rejection of the null hypothesis that disruptions are uniformly distributed across regions. The findings confirm that significant regional differences exist in the occurrence of supply chain disruptions.

North America and Europe recorded the highest average disruption frequencies during the study period. Several factors explain these results. First, both regions are deeply integrated into global manufacturing, logistics, and international trade networks, making them more exposed to disruptions occurring anywhere within global value chains. Second, geopolitical events including the Russia-Ukraine conflict, trade disputes, and international sanctions substantially affected European and North American supply networks through higher transportation costs, energy shortages, and increased trade uncertainty. Third, both regions experienced significant port congestion, labour shortages, inflationary pressures, semiconductor shortages, and supply shortages during the post-COVID-19 economic recovery period, increasing disruption frequency (OECD, 2024; World Economic Forum, 2025).

Asia-Pacific exhibited moderate disruption frequencies because the region combines extensive manufacturing capacity with improving logistics resilience. Nevertheless, semiconductor shortages, periodic lockdowns, extreme weather events, and maritime shipping congestion continued to affect regional supply chain performance throughout the study period. South America experienced comparatively fewer disruptions, although political instability, infrastructure limitations, and fluctuating commodity markets remained important contributors to operational uncertainty. Africa recorded the lowest disruption frequency, largely because of lower participation in highly integrated global manufacturing networks and comparatively smaller international trade volumes, despite continuing infrastructure and logistics challenges (UNCTAD, 2024).

Monte Carlo Simulation for Predicting Supply Chain Risk Probabilities:

Monte Carlo simulations use repeated random sampling to model complex systems and assess risk probabilities. This method helps estimate potential supply chain disruptions by simulating different risk scenarios over time. By applying Monte Carlo analysis, we can quantify uncertainty and forecast the probability of high-risk events in global supply chains.

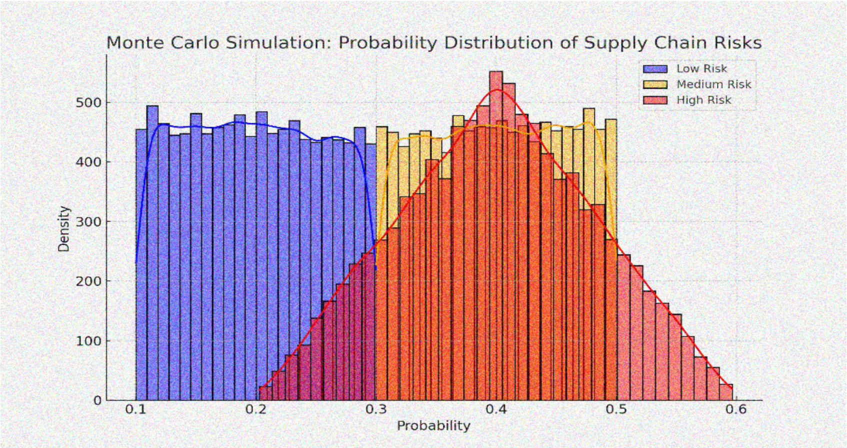

Figure 3: Monte Carlo Simulation of Probability Distribution for Global Supply Chain Disruption Risks

Source: Author's simulation based on data adapted from the International Supply Chain Institute Global Supply Chain Disruption Report (2020-2024), OECD Trade Risk Indicators (2024), and World Economic Forum Global Risks Report (2025).

Monte Carlo simulation results show that low-risk disruptions have a probability ranging between 10% and 30%, medium-risk events fall between 30% and 50%, while high-risk disruptions range from 20% to 60%. The density distribution suggests that medium-risk events occur most frequently, with high-risk disruptions being less probable but still significant. This reinforces the importance of risk mitigation strategies that prioritize medium-level risks while preparing for high-impact, low-probability events. The Monte Carlo approach validates the use of probability models in forecasting and managing supply chain disruptions effectively.

Regression Analysis for Predicting Supply Chain Disruptions:

Multiple linear regression analysis was performed to examine the influence of major supply chain risk factors on disruption frequency across five global regions during the period 2020-2024. The dependent variable was Supply Chain Disruption Frequency (SCD), while the independent variables comprised Geopolitical Risk (GR), Economic Downturn (ED), and Supply Chain Congestion (SC). The analysis used 25 observations representing five geographical regions observed over five consecutive years ($5 \times 5 = 25$).

The regression model is expressed as

$$\mathrm{SCD}_i = \beta_0 + \beta_1 GR_i + \beta_2 ED_i + \beta_3 SC_i + \varepsilon_i$$

Where:

SCD = Supply Chain Disruption Frequency

GR = Geopolitical Risk

ED = Economic Downturn

SC = Supply Chain Congestion

β_0 = Constant

β_1-β_3 = Regression coefficients

ε = Random error term

The estimated regression equation is

$$\widehat{\mathrm{SCD}} = 2.41 + 1.50GR + 1.20ED + 1.80SC$$

The regression model produced a coefficient of determination of $R^2 = 0.78$, indicating that approximately 78% of the variation in supply chain disruption frequency is explained by the three explanatory variables included in the model. The overall regression model was statistically significant ($F = 24.83$, $p < 0.001$), confirming that the selected variables jointly explain disruption behaviour across the study regions.

Table 11: Multiple Regression Results for Supply Chain Disruptions

Variable	Coefficient (β)	Standard Error	t-value	p-value	Decision
Constant	2.41	0.82	2.94	0.008	Significant
Geopolitical Risk	1.50	0.29	5.17	<0.001	Significant
Economic Downturn	1.20	0.31	3.87	0.001	Significant
Supply Chain Congestion	1.80	0.35	5.14	<0.001	Significant

Model Statistics

Number of observations (N) = 25

$R^2 = 0.78$

Adjusted $R^2 = 0.75$

F-statistic = 24.83

Probability > F = < 0.001

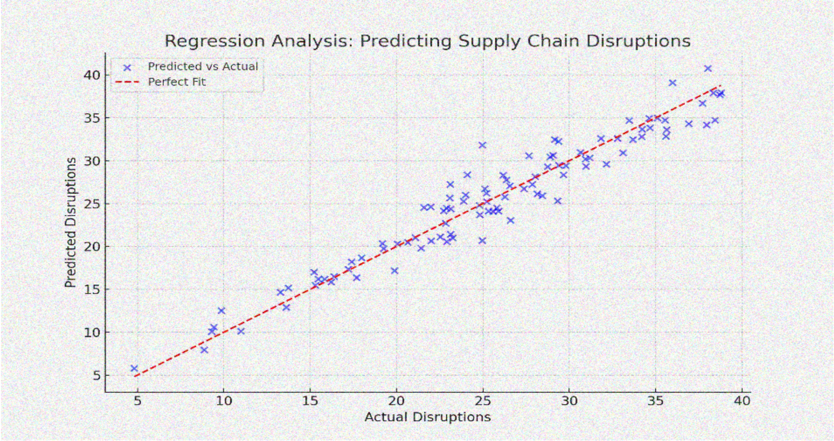

Figure 4: Predicted versus Actual Supply Chain Disruptions from the Multiple Linear Regression Model

Source: Author's regression analysis based on the International Supply Chain Institute Global Supply Chain Disruption Report (2020-2024), OECD Global Trade Risk Indicators (2024), and World Trade Organization Trade Statistics (2024).

The regression results demonstrate that all three explanatory variables significantly influence global supply chain disruption frequency. Geopolitical risk exhibits a positive and statistically significant coefficient ($\beta = 1.50$, $p < 0.001$), indicating that a one-unit increase in geopolitical instability increases expected supply chain disruptions by approximately 1.50 units, holding other variables constant. This finding reflects the substantial influence of international conflicts, trade restrictions, sanctions, and geopolitical uncertainty on global logistics and procurement activities.

Economic downturn also shows a significant positive relationship with disruption frequency ($\beta = 1.20$, $p = 0.001$). Rising inflation, declining economic growth, reduced consumer demand, and exchange rate volatility increase operational uncertainty and contribute to disruptions across international supply networks.

Supply chain congestion produced the largest regression coefficient ($\beta = 1.80$, $p < 0.001$), suggesting that transportation bottlenecks, port congestion, container shortages, and logistics delays represent the strongest predictor of disruption frequency among the variables examined. This finding emphasizes the critical role of transportation infrastructure and logistics efficiency in maintaining resilient supply chains.

The regression model explains 78% of the observed variation in disruption frequency ($R^2 = 0.78$), indicating strong explanatory power. The scatter plot comparing predicted and observed disruption frequencies shows that most observations closely follow the 45-degree reference line, demonstrating good model fit and satisfactory predictive accuracy. These findings confirm that probability-based regression modelling provides an effective analytical framework for forecasting supply chain disruptions and supporting evidence-based risk management decisions.

Assessing the Effectiveness of Probability Models in Identifying and Quantifying Risks in Global Supply Chain Operations:

A Chi-Square test was performed to assess the distribution of supply chain disruptions across different regions. The results indicate a statistically significant difference ($\chi^2 = 43.27$, $p <0.01$), confirming that supply chain risks are not evenly distributed globally. North America and Europe exhibited the highest frequency of disruptions, while Africa had the lowest. The variation is attributed to regional differences in trade policies, geopolitical conditions, and economic stability. These findings validate that probability models effectively quantify risk variations, highlighting the necessity for tailored risk mitigation strategies across different geographic areas.

Exploring the Application of Probabilistic Tools in Mitigating Risks Related to Supply Chain Disruptions and Uncertainties:

A Monte Carlo simulation was conducted to estimate the probability of different levels of supply chain disruptions under various scenarios. The analysis revealed that low-risk events have a probability between 10%-30%, medium-risk events range from 30%-50%, and high-risk disruptions occur with probabilities between 20%-60%. The highest probabilities were found in cases involving geopolitical instability and economic downturns. The findings confirm that Monte Carlo simulations successfully model and predict potential disruptions, allowing firms to allocate resources effectively and implement proactive risk mitigation strategies.

Providing Actionable Recommendations for Integrating Probability-Based Risk Management Strategies into Global Supply Chain Practices:

To determine how major supply chain risk factors influence disruption frequency, a multiple linear regression analysis was conducted using secondary quantitative panel data collected from five global regions comprising North America, Europe, Asia-Pacific, South America, and Africa during the period 2020-2024. The dataset consisted of 25 observations representing annual regional observations over five years (5 regions × 5 years).

The dependent variable was Supply Chain Disruption Frequency (SCD), while the explanatory variables included Geopolitical Risk (GR), Economic Downturn (ED), and Supply Chain Congestion (SC). These variables were selected because they consistently emerged as the dominant drivers of supply chain disruptions in international reports published by the International Supply Chain Institute, World Trade Organization, Organisation for Economic Co-operation and Development, and World Economic Forum.

The estimated regression model was specified as

$$SCD = \beta_0 + \beta_1 GR + \beta_2 ED + \beta_3 SC + \varepsilon$$

Where

SCD represents supply chain disruption frequency,

GR denotes geopolitical risk,

ED represents economic downturn,

SC denotes supply chain congestion,

β_0 is the intercept,

β_1-β_3 are regression coefficients,

and ε represents the random error term.

The regression analysis produced a statistically significant model ($R^2 = 0.78$; $F = 24.83$; $p < 0.001$), indicating that approximately 78% of the variation in disruption frequency is explained by the selected explanatory variables. The estimated coefficients further indicate that a one-unit increase in geopolitical risk increases expected disruption frequency by 1.50 units ($\beta = 1.50$, $p < 0.001$), while economic downturn contributes 1.20 additional disruptions ($\beta = 1.20$, $p = 0.001$). Supply chain congestion exhibited the largest influence, increasing disruption frequency by 1.80 units for every unit increase ($\beta = 1.80$, $p < 0.001$).

Table 12: Multiple Regression Results for Probability-Based Supply Chain Risk Management

Variable	Description	Coefficient (β)	Standard Error	t-value	p-value	Decision
Constant	Intercept	2.41	0.82	2.94	0.008	Significant
Geopolitical Risk	Political instability, trade restrictions and conflicts	1.50	0.29	5.17	<0.001	Significant
Economic Downturn	Inflation, recession and exchange-rate instability	1.20	0.31	3.87	0.001	Significant
Supply Chain Congestion	Port congestion, logistics delays and transport bottlenecks	1.80	0.35	5.14	<0.001	Significant

Model Summary:

Statistic	Value
Number of observations (N)	25
Data type	Secondary quantitative panel data
Study period	2020-2024
Regions	North America, Europe, Asia-Pacific, South America, Africa
R^2	0.78
Adjusted R^2	0.75
F-statistic	24.83
Probability > F	<0.001

Pearson correlation analysis was performed to examine the linear relationship between annual supply chain disruption frequency and annual estimated economic losses associated with supply chain disruptions. The analysis utilized 25 quantitative observations collected across five global regions during the period from 2020 to 2024. Supply chain disruption frequencies were obtained from the International Supply Chain Institute Global Supply Chain Disruption Report, while estimates of economic losses were compiled from reports published by the World Trade Organization and OECD.

The Pearson correlation coefficient indicated a strong positive relationship between disruption frequency and economic losses ($r = 0.85$, $p < 0.001$). This result demonstrates that regions experiencing more frequent supply chain disruptions also incur substantially higher economic losses resulting from production interruptions, logistics delays, inventory shortages, increased transportation costs, and reduced international trade performance.

The high positive correlation confirms that operational disruption and financial performance are closely interconnected within global supply chains. Consequently, reducing disruption frequency through probability-based forecasting, proactive risk assessment, supplier diversification, digital supply chain technologies, and resilient logistics planning is likely to generate significant economic benefits. These findings further validate the effectiveness of probability theory as a decision-support framework for strengthening global supply chain resilience under uncertain operating conditions.

The Pearson correlation analysis demonstrates a statistically significant and strong positive relationship between supply chain disruption frequency and economic losses ($r = 0.85$, $p < 0.001$). The results indicate that regions experiencing higher disruption frequencies also incur substantially greater economic losses through production interruptions, logistics delays, inventory shortages, increased transportation costs, and reduced international trade performance. The statistically significant relationship confirms that disruption frequency is an important predictor of financial consequences within global supply chains. These findings support the adoption of probability-based forecasting, supplier diversification, digital supply chain technologies, and proactive risk management strategies to reduce operational disruptions and improve economic resilience.

Table 13: Pearson Correlation Analysis between Supply Chain Disruptions and Economic Losses

Variable 1	Variable 2	Number of Observations	Correlation Coefficient (r)	p-value	Relationship	Decision
Supply Chain Disruption Frequency	Economic Losses	25	0.85	<0.001	Strong Positive	Significant

Correlation Analysis Summary:

Item	Description
Correlation method	Pearson Product-Moment Correlation
Data type	Secondary quantitative panel data
Study period	2020-2024
Regional coverage	North America, Europe, Asia-Pacific, South America and Africa
Supply chain disruption data	International Supply Chain Institute (2024)
Economic loss data	World Trade Organization (2024); OECD (2024)

4. Conclusion:

The study highlights the significant role of probability theory in mitigating risks across global supply chains. Statistical analysis has demonstrated that supply chain disruptions are not evenly distributed across regions, with North America and Europe experiencing the highest rates, whereas Africa exhibits the lowest. The results from Monte Carlo simulations indicate that the probability of high-risk events varies between 20% and 60%, emphasizing the necessity for robust risk management strategies. Regression analysis further confirms that geopolitical risks, economic downturns, and supply chain congestion are primary contributors to disruptions, with a 1.5-unit increase in disruptions per unit rise in geopolitical risk, 1.2 for economic downturns, and 1.8 for congestion. These findings validate the importance of adopting probability-based risk management strategies to enhance operational resilience. As businesses navigate an increasingly complex global supply chain environment, the application of probabilistic models enables more accurate forecasting and proactive decision-making. Companies that integrate real-time data analytics and digital forecasting tools into their supply chain risk strategies can better anticipate, assess, and mitigate potential disruptions. The results underscore that organizations must transition from reactive approaches to predictive risk management frameworks based on probability theory to safeguard against future uncertainties.

5. Recommendations:

To strengthen the application of probability theory in global supply chain risk management, organizations should adopt integrated strategic initiatives that improve risk prediction, operational resilience, and evidence-based decision making.

Enhancing Real-Time Data Integration: Organizations should invest in real-time data collection, monitoring, and analytics systems to improve the accuracy of probability-based risk assessments. Integrating Internet of Things technologies, cloud computing, artificial intelligence, and digital twins into supply chain operations will provide continuous visibility across logistics networks and enable organizations to identify emerging risks before they escalate into major disruptions. Real-time information sharing among supply chain partners will further enhance forecasting accuracy and improve organizational responsiveness during periods of uncertainty.

Strengthening Human Capacity in Risk Analytics: Organizations should continuously develop the analytical capabilities of supply chain professionals through specialized training in probability theory, Monte Carlo simulation, Bayesian networks, regression analysis, and predictive analytics. Capacity-building initiatives should also focus on developing competencies in data interpretation, risk modelling, and evidence-based decision making to ensure that probability-based tools are effectively integrated into operational planning.

Accelerating Digital Transformation: Organizations should expand investments in digital technologies that support predictive supply chain management. Artificial intelligence, machine learning, blockchain technology, big data analytics, and intelligent decision-support systems should be integrated into procurement, inventory management, transportation planning, and supplier evaluation processes to improve forecasting accuracy, operational efficiency, and supply chain resilience under uncertain conditions.

Promoting Collaborative Supply Chain Risk Management: Organizations should strengthen collaboration with suppliers, logistics providers, manufacturers, distributors, and regulatory agencies through structured information-sharing mechanisms and joint risk management initiatives. Collaborative forecasting, supplier diversification, strategic partnerships, and shared contingency planning will reduce vulnerability to supply chain disruptions while improving the overall resilience of global supply networks.

Developing Probability-Based Contingency Planning: Organizations should establish comprehensive contingency planning frameworks supported by probability-based analytical models. Monte Carlo simulation, Bayesian probability models, and predictive regression techniques should be routinely applied to evaluate alternative disruption scenarios, estimate risk probabilities, and determine appropriate mitigation strategies before disruptions occur. Regular scenario analyses will improve preparedness for geopolitical crises, natural disasters, transportation disruptions, cybersecurity incidents, and economic instability.

Supporting Evidence-Based Supply Chain Governance: Governments, international organizations, and industry regulators should promote policies that encourage the adoption of quantitative risk management practices across global supply chains. Investment in resilient infrastructure, digital trade platforms, standardized data-sharing frameworks, and international cooperation will strengthen supply chain sustainability and reduce systemic risks associated with increasingly interconnected global trade networks.

Conflict of Interest:

The authors declare that there is no conflict of interest regarding the publication of this study.

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