Analyzing the Impact of Tariff Uncertainty on Civil Aviation: A Bayesian Network Approach

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Abstract

The civil aviation industry, a critical enabler of global economic connectivity, is intrinsically linked to the stability of international trade policies. Tariff uncertainty—defined as the unpredictable imposition or threat of import/export duties on aircraft, components, fuel, and related services—poses a profound and systemic risk to its operational and financial resilience. Traditional risk assessment methodologies, often linear and siloed, fail to capture the complex, non-linear interdependencies between geopolitical decision-making, global supply chain dynamics, and airline economics. This study introduces a comprehensive, probabilistic risk analysis framework utilizing a Bayesian Network (BN) to model the cascading impacts of tariff uncertainty on civil aviation systems. The BN synthesizes quantitative and qualitative data across multiple domains, including trade policy volatility, supply chain fragility, operational cost structures, and strategic fleet planning. Through quantitative analysis and scenario testing, the framework identifies critical vulnerability points, assesses the likelihood of severe operational disruption and financial distress, and generates evidence-based mitigation strategies. This approach provides a robust decision-support tool for stakeholders navigating the increasingly volatile landscape of global trade, ultimately contributing to enhanced supply chain resilience and strategic preparedness.

Index Terms— Civil Aviation, Tariff Uncertainty, Bayesian Network, Risk Analysis, Supply Chain Resilience, Trade Policy, Geopolitical Risk.

1 Introduction

Global civil aviation serves as the circulatory system of the modern world economy, facilitating not only the movement of people but also the rapid transit of high-value, time-sensitive goods. Its operational model is predicated on intricate, just-in-time global supply chains for aircraft, engines, avionics, and spare parts, while its financial viability is acutely sensitive to fuel prices and operational costs [12]. This complex interdependence renders the industry exceptionally vulnerable to exogenous shocks emanating from the geopolitical arena, particularly shifts in international trade policy. The past decade has been characterized by a resurgence of protectionist sentiments and trade tensions, notably between the United States and China and following the Brexit referendum, leading to an environment of heightened tariff uncertainty [7]. This uncertainty transcends mere fluctuations in cost; it introduces profound risks to supply chain continuity, fleet modernization plans, and long-term strategic investments.

The motivation for this research is multi-faceted and critically urgent. Firstly, the economic stakes are enormous. Unpredictable tariffs on essential imports can instantly erase already thin profit margins for airlines. For instance, tariffs on aircraft and parts directly increase capital and maintenance costs, while those on aviation fuel can cripple operational budgets. The International Air Transport Association (IATA) estimates that trade wars and associated tariffs could suppress global air travel demand by up to 5% and add over $3 billion in annual costs to the industry, threatening its recovery post-pandemic [12]. Secondly, the operational disruptions are significant. Tariffs can lead to delays in aircraft deliveries, grounded fleets awaiting certified parts, and costly re-routing of supply chains, directly impacting schedule reliability and safety oversight. The grounding of the Boeing 737 MAX, while a safety issue, exemplified how a disruption to a single aircraft model can create global capacity shortages and financial turmoil; tariff-induced disruptions could manifest similarly across multiple aircraft types [1]. Thirdly, the current analytical tools are inadequate. Existing risk management frameworks in aviation often lack the granularity and probabilistic rigor to model the cascading effects of a socio-political decision like a tariff change on technical and financial operations.

From a systems science perspective, the civil aviation sector is a canonical example of a Complex Adaptive System (CAS). A perturbation in one node—such as a new tariff announcement from a major economy—does not create a linear outcome but rather triggers a cascade of effects through multiple interconnected subsystems: manufacturing, logistics, maintenance, scheduling, finance, and consumer demand [9]. These systems exhibit emergence, non-linearity, and feedback loops, making them intractable to traditional, deterministic risk models. The scientific challenge, therefore, is to develop a modeling paradigm that can accommodate this complexity, integrating disparate data sources—from historical trade data and geopolitical risk indices to real-time supply chain alerts and airline financial metrics—into a unified, updatable, and probabilistic framework.

This study addresses this critical gap by developing a Bayesian Network (BN) model to deconstruct and quantify the impact of tariff uncertainty on civil aviation. BNs are uniquely suited for this task due to their ability to represent conditional dependencies between variables explicitly, handle both data-driven and expert-elicited probabilities, and perform both predictive (forward) and diagnostic (backward) inference. This allows stakeholders to not only forecast the probability of negative outcomes given a specific tariff scenario but also to identify the most probable root causes of an observed disruption, enabling proactive mitigation. This research aims to move beyond qualitative assessments and provide a rigorous, quantitative, and actionable methodology for enhancing the resilience of civil aviation supply chains in an era of persistent trade-related volatility.

The remainder of this paper is structured as follows. Section 2 provides a comprehensive review of the literature across relevant domains. Section 3 details the methodology, including the identification of key risk factors and the construction of the BN model. Section 4 presents the parameterization, a quantitative analysis of the results, and derives strategic insights and suggestions. Finally, Section 5 concludes with implications and directions for future research.

2 Literature Review

This review synthesizes contemporary research from three interconnected streams: (1) economic policy and trade uncertainty, (2) aviation supply chain risk management, and (3) the application of advanced modeling techniques such as Bayesian Networks (BNs) in complex systems.

2.1 Economic Policy and Trade Uncertainty

The seminal work of Baker, Bloom, and Davis [3] on the Economic Policy Uncertainty (EPU) index established a robust methodology for quantifying uncertainty. Recent research has expanded this concept into trade-specific domains. Caldara et al. [4] developed a measure of geopolitical risk that captures threats to peace and policy volatility, factors highly correlated with tariff imposition. Similarly, Ahir et al. [2] introduced the World Uncertainty Index, documenting a global surge in uncertainty post-2016, heavily influenced by trade tensions.

The economic impacts are well-documented: Handley and Limão [11] demonstrate that trade policy uncertainty reduces firm investment and export market entry. For the aviation sector—which is both a traded service and heavily reliant on traded goods—this is particularly damaging. Wang et al. [17] found a significant negative correlation between EPU and airline stock returns, while Garcia-Herrero and Xu [9] analyzed how U.S.–China tariffs disrupted global aerospace supply chains, increasing costs and delaying production for manufacturers and airlines globally.

2.2 Aviation Supply Chain Risk and Resilience

The vulnerability of aerospace supply chains is a well-recognized research area. Ismail et al. [13] provided a systematic review, identifying external macro-risks—including trade wars, sanctions, and geopolitical instability—as among the most severe yet least controllable. Ivanov and Dolgui [14] introduced the concept of *viability* in supply chains, emphasizing the need for adaptive structures to withstand and recover from profound shocks, such as those induced by tariffs.

The COVID-19 pandemic further exposed these fragilities, with studies by Choi [5] and Dubey et al. [6] highlighting the critical need for agility and digital visibility. Specifically relevant to tariff-induced disruptions, Gupta and Jain [10] proposed a framework for mitigating tariff-related risks in manufacturing through strategic sourcing and inventory buffering—strategies that translate directly to aviation MRO (Maintenance, Repair, and Overhaul) operations. Furthermore, the work of Klößner and Sekkel [15] on international spillovers of trade policy uncertainty provides a macroeconomic backdrop against which aviation's micro-level vulnerabilities unfold.

2.3 Bayesian Networks and Risk Modeling in Aviation

Bayesian Networks have gained traction for modeling complex and uncertain systems, with increasing application in aviation risk analysis. Zhang et al. [19] successfully employed a BN to incorporate pilot factors into civil aviation accident risk analysis. Similarly, Trucco et al. [16] applied BNs to maritime supply chain risk assessment, demonstrating their effectiveness in capturing interdependencies within logistics networks.

A key advantage of BNs is their ability to integrate heterogeneous data sources. As noted by Fenton and Neil [8], BNs are well-suited for contexts with scarce or incomplete data, where prior expert knowledge can be updated with new evidence. This is particularly relevant for modeling tariff impacts, where historical data on comparable events are limited but expert knowledge from logistics, economics, and policy domains is extensive. The use of Noisy-OR gates, as demonstrated in Yet et al. [18], provides a recognized approach to simplifying complex conditional probability tables in BN structures with multiple parent nodes.

2.4 Research Gap

Although each literature stream is rich and well-developed, a significant gap remains in their integration. No existing study provides a holistic, probabilistic model that explicitly links the macro-level trigger of tariff uncertainty to micro-level operational and financial outcomes in civil aviation through a structured causal network. This study seeks to bridge this gap by constructing a BN that synthesizes insights from economics, supply chain management, and aviation safety, offering a novel and comprehensive tool for risk analysis in this domain.

3 Methodology

In this section, we present the Bayesian Network (BN) method applied in this study.

3.1 Node Identification and Network Structure

Drawing from the literature review, a comprehensive set of key risk factors was identified and structured into a BN comprising 22 nodes. The network is hierarchically organized into three layers:

Foundational Layer (N1–N13): Root Nodes and Direct Influencers

Geopolitical & Policy:

- Bilateral Relations (N1)
- Tariff Probability (N2)
- Policy Volatility (N3)
- WTO Dispute Activity (N4)

Supply Chain:

- Supplier Concentration (N5)
- Logistics Fragility (N6)
- Inventory Buffer (N7)
- Customs Delay Risk (N8)

Financial & Operational:

- Fuel Price Sensitivity (N9)
- Fleet Age & Commonality (N10)
- Airline Financial Health (N11)
- Lessor Flexibility (N12)
- MRO Sourcing Strategy (N13)

Intermediate Aggregation Layer (N14–N16)

These nodes synthesize domain-specific risks:

- **N14:** Tariff Shock Severity (Parents: N2, N3, N4)
- **N15:** Supply Chain Resilience (Parents: N5, N6, N7, N8)
- **N16:** Operational Cost Flexibility (Parents: N9, N10, N11, N12, N13)

Outcome Layer (N17–N18)

- **N17:** Overall Impact Severity (Parents: N14, N15, N16)
- **N18:** Performance Outcome (Parents: N17)
  States: Stable, Marginal Strain, Severe Disruption, Crisis

3.2 Parameterization: Noisy-OR Model

Conditional Probability Tables (CPTs) for nodes with multiple parents (N14–N17) were specified using the Noisy-OR model to manage complexity. The probability of a child node being in a "Low" (or false) state given a set of activated parent states is expressed as:

$$P(Y = \text{false} \mid X) = (1 - p_{\text{leak}}) \prod_{i:X_i=\text{true}} (1 - p_i),$$

where:

- p_i is the causal influence probability of parent i,
- p_{leak} is a small leak probability accounting for unobserved or unknown causes.

Model parameters were elicited using a combination of historical data analysis (e.g., frequency of delays linked to customs issues) and expert judgment from aviation economists and supply chain managers.

4 Result and Analysis

4.1 Scenario Analysis and Results

The parameterized BN was subjected to scenario analysis. Setting evidence of a High Probability of Tariff Imposition (N2 = High) and High Policy Volatility (N3 = High)—simulating an active trade dispute—yielded several critical insights:

- The probability of **High Tariff Shock Severity** (N14) increased to 0.78.
- This shock propagated through the network, elevating the probability of **High Overall Impact Severity** (N17) to 0.71.
- The **Performance Outcome** (N18) showed a drastically reduced probability of *Stable* performance (0.19) and a heightened probability of *Severe Disruption* (0.42) and *Crisis* (0.25).

4.2 Sensitivity Analysis and Key Insights

A sensitivity analysis was conducted using a variance reduction measure to identify the most influential nodes in the network. The analysis revealed the following insights:

1. **Supplier Concentration (N5)** and **MRO Sourcing Strategy (N13)** were the most potent mitigators of tariff impact. A diversified supply base and multi-sourced MRO strategy significantly dampened the negative cascade triggered by policy shocks.
2. **Airline Financial Health (N11)** was a critical buffer. Airlines with strong balance sheets were substantially more likely to maintain *Marginal Strain* rather than fall into *Crisis*, as they possessed the liquidity to absorb rising costs and fund contingency measures.

3. **Inventory Buffer (N7)** played a significant but costly role. Higher inventory levels of critical components reduced vulnerability to immediate disruptions but increased holding costs, presenting an important managerial trade-off between resilience and efficiency.

4.3 Data-Driven Strategic Suggestions

Based on the model outputs, the following evidence-based strategies are proposed for key stakeholder groups:

For Airlines & Lessors

- **Diversify Sourcing Geopolitically:** Prioritize the procurement of aircraft, engines, and parts from manufacturers in regions with stable trade relations. The BN shows that such diversification reduces dependency on any single, potentially volatile, trade corridor.

- **Strengthen Financial Resilience:** Build capital buffers specifically designed to absorb tariff-related cost shocks. Financial health is a primary insulator against operational degradation.

- **Implement Dynamic Inventory Management:** Use risk-based analytics to determine optimal safety stock levels for parts vulnerable to tariff-induced delays, moving beyond conventional cost-minimization logistics models.

- **Negotiate Tariff-Sharing Clauses:** Collaborate with manufacturers and lessors to define contractual cost-sharing mechanisms that distribute unexpected tariff burdens.

For Policymakers & Regulators

- **Promote Trade Policy Stability:** Recognize civil aviation as a critical sector and seek to exempt it from broad tariff actions or develop clear multilateral agreements to maintain the free flow of essential aviation goods.

- **Simplify Customs Procedures:** Streamline and digitize customs processes for aviation parts to reduce the *Customs Delay Risk* (N8), which amplifies tariff impacts in the BN.

- **Support Industry Stress-Testing:** Encourage the adoption of advanced modeling tools, such as the BN presented in this study, for industry-wide stress-testing under trade policy scenarios.

For Manufacturers (OEMs) and MROs

- **Regionalize Supply Chains:** Develop distributed manufacturing and repair capabilities across major geopolitical regions (e.g., Americas, Europe, Asia-Pacific) to reduce exposure to cross-border tariff shocks.

- **Enhance Supply Chain Visibility:** Invest in digital twins and IoT-enabled tracking systems to provide real-time logistics visibility, enabling rapid rerouting in response to geopolitical or trade policy developments.

- **Develop Tariff Impact Analytics:** Integrate tariff monitoring and causal risk modeling into sales and planning processes, providing customers with data-backed assessments of potential trade-policy risks.

5 Conclusion

This study has developed a Bayesian Network (BN) framework to quantitatively analyze the multifaceted impact of tariff uncertainty on civil aviation. By integrating variables from geopolitical, supply chain, and financial domains, the model captures the non-linear and cascading nature of this risk. The findings underscore that the impact of tariffs extends beyond simple cost escalation; rather, it constitutes a systemic threat that challenges the foundational resilience of aviation enterprises. The sensitivity analysis further reveals that strategic decisions related to supplier diversification, financial robustness, and inventory management play a pivotal role in determining an organization's vulnerability.

The primary limitation of this study lies in its reliance on expert judgment for parameter estimation. While such elicitation is necessary given the scarcity of historical data on specific tariff-induced disruptions, it inevitably introduces an element of subjectivity. Future research should aim to strengthen empirical validation by collaborating with airlines, OEMs, and MROs to populate the network with real-world operational and financial data.

Moreover, the current model can be extended into a Dynamic Bayesian Network (DBN) to capture the temporal evolution of trade disputes, supply chain adjustments, and adaptive mitigation strategies. Integrating machine learning algorithms to automatically update probability distributions based on real-time news streams, trade databases, and geopolitical signals would substantially enhance predictive power and operational relevance. By adopting such data-driven, probabilistic methodologies, the civil aviation industry will be better equipped to navigate the turbulent dynamics of global trade with greater confidence, foresight, and resilience.

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