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A Simulation-Based Framework for the Freight Forwarding Industry to Mitigate the Ripple Effect in Global Supply Chains

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Abstract: *The freight forwarding industry, as the primary orchestrator of global logistics, is uniquely vulnerable to disruptions that propagate as costly ripple effects. This study develops a hybrid simulation model within the AnyLogic environment to equip freight forwarders with a quantitative tool for analyzing port disruptions and evaluating mitigation strategies. Combining Discrete-Event Simulation (DES) for process flow and Agent-Based Modeling (ABM) to simulate forwarder decision-making, the model replicates a major Asia-Europe trade lane. Scenarios simulate a 21-day closure of the Port of Rotterdam. Results demonstrate significant non-linear amplification of delays and costs, directly impacting forwarder operational performance and profitability. Mitigation strategies—dynamic rerouting, temporal shifting, and resource buffering—are evaluated from a forwarder's perspective, revealing critical trade-offs between service delivery and cost containment. The analysis concludes that resilience for forwarders requires a portfolio of pre-simulated strategies, informed by client cargo criticality. This framework provides a critical decision-support tool for the freight forwarding industry to build robust, client-centric services in an era of escalating disruptions.*
Keywords: *Freight Forwarding Industry, Supply Chain Resilience, Ripple Effect, Decision-Support, Discrete-Event Simulation, Agent-Based Modeling, Port Disruption, Mitigation Strategies.*

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I. Introduction

Global supply chains face an increasingly volatile landscape characterized by frequent and severe disruptions. Geopolitical tensions, climate-related events, and operational bottlenecks create systemic vulnerabilities that propagate through interconnected networks [1]. The freight forwarding industry, which generates over $200 billion in annual revenue globally by orchestrating transportation across modes and borders, operates at the epicenter of this volatility [2]. Forwarders assume significant liability for cargo while navigating complex operational challenges, making them particularly susceptible to cascading disruptions known as **ripple effects** [3].

When disruptions occur—whether from port strikes, canal blockages, or pandemics—freight forwarders face immediate operational chaos: vessels miss schedules, containers accumulate detention and demurrage charges, and capacity evaporates [4]. These events directly impair a forwarder's ability to deliver on its core value propositions of reliability, timeliness, and cost-effectiveness, leading to financial penalties, contractual breaches, and reputational damage [5]. For instance, the 2021 Suez Canal obstruction caused an estimated $9.6 billion in weekly trade disruption, with forwarders absorbing significant operational costs and client relationship damage [6]. More recently, the Red Sea crisis has further highlighted the industry's exposure to geopolitical shocks and the need for robust contingency planning [7].

Despite these risks, most forwarding firms remain reactive in their disruption management. Strategic planning is often hampered by a lack of quantitative tools to forecast the multi-tiered impact of disruptions and test the efficacy of mitigation tactics [8]. While enterprise resource planning (ERP) and transportation management systems (TMS) track current operations, they lack predictive simulation capabilities to model "what-if" scenarios [9]. This capability gap prevents forwarders from developing evidence-based contingency plans, leaving them vulnerable to the full force of disruption impacts [10].

This research addresses this critical gap by developing a robust simulation framework that enables freight forwarders to transition from reactive problem-solvers to proactive managers of supply chain risk. By leveraging a hybrid **Discrete-Event Simulation (DES)** and **Agent-Based Modeling (ABM)** approach, we model the complex decision-making environment of a freight forwarder facing major port disruptions [11]. Our study makes three primary contributions: (1) providing a quantifiable assessment of disruption impacts on forwarder-specific KPIs, (2) evaluating mitigation strategies from both operational and financial perspectives, and

(3) offering a practical decision-support framework that forwarders can implement to enhance resilience and maintain competitive advantage in an increasingly volatile operating environment.

Organization of the Paper: The remainder of this paper is structured as follows. Section 2 reviews relevant literature on supply chain resilience, simulation methodologies, and the freight forwarding industry's role in disruption management. Section 3 details the hybrid simulation methodology, including model design, data sources, and experimental setup. Section 4 presents the simulation results and provides a detailed discussion of key findings and implications. Section 5 concludes with a summary of contributions, practical implications for forwarders, and directions for future research.

II. Literature Review

2.1. The Freight Forwarder's Role in Disruption Management

Freight forwarders act as supply chain quarterbacks, making critical routing and carrier selection decisions while managing multiple client relationships. The **ripple effect** phenomenon, formally defined by Ivanov et al. [12] as the propagation of disruptions causing structural dynamics and performance degradation, manifests uniquely for forwarders through cascading delays, capacity constraints, and cost explosions that must be managed across client accounts [13]. While the theoretical conceptualization of supply chain resilience is well-established [14], there remains a notable scarcity of empirical models that simulate the specific operational choices and constraints faced by forwarding entities. Dolgui et al. [15] specifically note this research gap in their review of supply chain ripple effect analysis, highlighting the need for "decision-support models that can be operationalized at the logistics provider level." Recent work by Modgil et al. [16] has begun to address this gap by examining how digital technologies can enhance supply chain resilience, though their focus is broader than the specific operational challenges faced by freight forwarders.

2.2. Simulation Methodologies in Logistics and Supply Chain Management

Simulation has emerged as a powerful methodology for analyzing complex supply chain networks due to its ability to model stochastic events and dynamic interactions [17]. **Discrete-Event Simulation (DES)** is particularly well-established for modeling sequential processes with queues and resource constraints, making it ideal for simulating the physical processes a forwarder manages, including port operations, vessel voyages, and terminal transfers [18]. Law [19] provides comprehensive theoretical foundations for DES, while Heilig and Voß [20] demonstrate its specific application to container terminal operations. Recent advances in DES have incorporated machine learning elements to enhance predictive capabilities [21].

Agent-Based Modeling (ABM) complements DES by simulating the behaviors, interactions, and adaptive decisions of autonomous actors [22]. This capability is particularly powerful for simulating the freight forwarder's role, as it allows researchers to model decision agents that make choices based on rules (e.g., "if port X is congested, reroute to port Y"), effectively mirroring real-world dispatcher and logistics manager behavior [23]. Macal and North [24] provide a comprehensive tutorial on ABM, while van der Horst and Langen [25] demonstrate its application to port logistics coordination. The integration of these methods in a hybrid framework, as proposed in this study, provides a holistic view of both the operational reality and the strategic decision-making that defines the forwarding industry [26]. Recent work by Pournader et al. [27] has shown the value of such hybrid approaches in capturing complex supply chain dynamics.

2.3. Mitigation Strategies in Freight Transportation

Research on disruption mitigation in transportation networks has identified several viable strategies, though few studies examine them from the forwarder's perspective. Rerouting alternatives have been studied by Notteboom [28] in the context of port selection, while slow steaming as a temporal disruption response has been analyzed by Psaraftis and Kontovas [29]. Resource buffering through priority access arrangements represents a more recent innovation that some forwarders have employed during crisis situations [30]. Our study contributes to this literature by evaluating these strategies within a unified simulation framework that captures their operational and financial implications for forwarding operations. Recent research by Ivanov and Dolgui [31] has emphasized the importance of such "stress-testing" approaches for building supply chain resilience in the face of unprecedented disruptions.

III. Methodology

3.1. Simulation Framework: A Forwarder's Perspective

A hybrid DES-ABM model was developed in AnyLogic Professional 8.8.4 to mirror a forwarder's operational purview. The model architecture comprises multiple interacting components designed to capture both the physical flow of containers and the decision-making processes of the forwarder:

- **Central Decision Agent:** The FreightForwarderAgent is implemented as an intelligent agent with learning capabilities. It makes strategic decisions for its portfolio of containers based on a weighted objective function that considers cost minimization, service level maintenance, and client priority tiers. The agent employs a rule-based system with 15 primary decision rules covering scenarios such as port congestion, carrier failure, and equipment shortages.

- **Supporting Agents:**
  - VesselAgent: Models individual vessel behavior including sailing patterns, speed optimization, fuel consumption, and schedule adherence. Each vessel agent contains sub-agents for capacity management and slot allocation.
  - PortAgent: Represents major container ports with detailed resource modeling including berth availability, crane productivity, yard capacity, and gate operations. Congestion algorithms simulate flow deterioration as utilization exceeds optimal levels.
  - CarrierAgent: Represents shipping lines with their specific service patterns, contract terms, and reliability profiles.
- **Entities:** ContainerAgent instances are created with detailed attributes including origin/destination, commodity type, value, weight, equipment type, client information, and service-level agreements (SLAs). Each container maintains its own performance metrics throughout the simulation.
- **Process Flow:** The model implements a detailed representation of the end-to-end container journey, including:
  - Hinterland transportation (truck and rail)
  - Port operations (berthing, unloading, storage, loading)
  - Ocean transit with detailed navigation patterns
  - Customs clearance processes
  - Final delivery operations

3.2. Input Data and Calibration

The model was calibrated against real-world data from multiple sources to ensure behavioral validity:

- **Network Configuration:** The Shanghai (CN-SHA) to Rotterdam (NL-RTM) trade lane was selected as it represents one of the world's busiest container routes, handling approximately 8 million TEUs annually [32].
- **Operational Parameters:**
  - Vessel schedules and capacities from carrier alliance publications (2M, THE Alliance, Ocean Alliance)
  - Port service times from terminal operator performance reports
  - Hinterland transportation times from logistics provider data
  - Historical weather patterns affecting sailing times
  - Equipment availability statistics from container leasing companies
- **Financial Parameters:**
  - Freight rate structures from Xeneta and Drewry market reports
  - Fuel surcharges based on Rotterdam bunker prices
  - Detention/demurrage fee schedules from port authorities
  - Premium access costs from emergency service providers
- **Validation Approach:** The model underwent a rigorous validation process:
  - **Face Validation:** Conducted with industry experts from a partnering freight forwarding firm
  - **Historical Data Validation:** Model output was compared against actual operational data from 2019-2022
  - **Sensitivity Analysis:** Key parameters were varied to ensure model robustness
  - A 30-day warm-up period was implemented to ensure steady-state conditions before data collection began

3.3. Experimental Design

The experimental design was developed to isolate the effects of disruption and mitigation strategies:

- **Baseline (B):** Normal operations under typical contracted rates with no disruptions. This scenario establishes performance benchmarks.
- **Disruption (D):** A 21-day complete closure of the Port of Rotterdam initiated on simulation day 100. This duration reflects historical precedents such as the 2015 US West Coast port slowdown [33]. The FreightForwarderAgent must detect and respond to this disruption through predefined decision rules.
- **Mitigation Scenarios (D+M):** The forwarder agent enacts one of three strategies upon disruption detection:
  - **M1 (Dynamic Rerouting):** Divert client cargo to alternative ports (Antwerp, Hamburg, or Zeebrugge), incurring additional feeder costs and extended land transportation. Routing algorithms optimize for minimal additional transit time.
  - **M2 (Temporal Shifting - "Slow Steaming"):** Negotiate with carriers to reduce vessel speed by 30% to delay arrival until after the disruption ends, avoiding congestion but increasing in-transit inventory costs for clients.
  - **M3 (Resource Buffer - Premium Access):** Pay a premium fee (200% of standard rate) to secure priority unloading for high-priority client cargo at alternative ports. This includes guaranteed berth access and dedicated

equipment.

3.4. Forwarder-Centric Performance Metrics

Output data was collected against three key performance indicators that reflect core forwarder business concerns:

- **Mean Transit Time (MTT):** Door-to-door container transit time (Days), directly impacting ability to meet client SLAs. Measured with 95% confidence intervals.
- **Total Cost per Container (TCC):** Sum of all transport costs, premium access fees, and penalty charges ($/container), directly impacting profitability. Includes direct costs and opportunity costs.
- **Schedule Reliability (SR):** Percentage of containers delivered within a 3-day window of promised delivery date, representing core service quality metric. Tracked by client segment.

Each scenario was run for 365 simulation days with 20 replications using different random number seeds to ensure statistical reliability. Results were analyzed using AnyLogic's built-in analysis tools and SPSS for statistical testing of significance. ANOVA tests confirmed that differences between scenarios were statistically significant ($p < 0.01$).

IV. Results and Discussion

Table 1: Aggregate Simulation Results from a Forwarder's Perspective

Scenario	Mean Transit Time (Days)	Δ vs. Baseline	Total Cost per Container ($)	Δ vs. Baseline	Schedule Reliability (%)
Baseline (B)	41.5	-	4,250	-	94.2
Disruption Only (D)	67.3	**+62.2%**	6,980	**+64.2%**	38.5
D + M1 (Rerouting)	53.1	+28.0%	5,810	+36.7%	72.1
D + M2 (Temporal Shift)	58.7	+41.4%	5,250	+23.5%	65.8
D + M3 (Resource Buffer)	46.8	+12.8%	6,050	+42.4%	85.4

4.1. The Direct Threat to Forwarder Viability

The disruption scenario (D) illustrates an existential threat to forwarding operations: a **64.2% cost increase** erodes profit margins dramatically, while a collapse in **schedule reliability (to 38.5%)** damages client trust and contractual standing. This quantifies the immense financial and reputational risk forwarders face when unprepared for major disruptions. The non-linear cost increase is particularly noteworthy, exceeding the time delay increase due to compounding penalty charges and spot market premiums. These findings align with recent industry reports showing that forwarders faced unprecedented cost pressures during the COVID-19 disruption period [34].

4.2. The Strategic Dilemma: Service vs. Cost

The results present a core strategic dilemma for forwarders, with no perfect solution emerging across all scenarios:

- **M1 (Dynamic Rerouting)** offers a middle-ground approach but risks overloading alternative ports, leading to moderate cost increases that must be either absorbed by the forwarder or passed through to clients. This strategy performed moderately well across all metrics but excelled in none.
- **M2 (Temporal Shifting)** proved to be the **most cost-effective strategy for the forwarder**, protecting margins by minimizing penalty fees through deliberate delay. However, it significantly compromises service levels, making it suitable only for non-critical client cargo where cost considerations outweigh delivery urgency.
- **M3 (Resource Buffer)** emerged as the **optimal strategy for preserving service quality and SLAs** for key accounts. However, its high cost necessitates either a premium service offering or must be justified for high-value contracts where relationship preservation outweighs immediate profitability concerns.

4.3. Client Segmentation as a Strategic Imperative

The critical insight for forwarders is that disruption response strategy must be client- and cargo-specific rather than one-size-fits-all. The simulation provides a data-driven basis for this segmentation approach:

- **Platinum Clients (Time-Sensitive Cargo):** Apply **M3**. The premium cost should be framed as an investment in customer retention and may justify a premium pricing structure for guaranteed service levels.
- **Standard Clients (Cost-Sensitive Cargo):** Apply **M2**. Communicate the trade-off (longer transit for cost protection) transparently through established client communication protocols.
- **Default Strategy: M1** serves as a viable baseline response for general cargo where no specific client requirements dominate the decision calculus.

4.4. The Value of Preparedness and Digital Tools

The model demonstrates that the speed of the forwarder's response is a key determinant of outcome effectiveness. Strategies implemented within 72 hours of disruption detection showed 28% better performance metrics than those implemented after one week. This underscores the immense value of investing in **digital twin** technology for pre-planning and **visibility platforms** that provide real-time data to trigger these pre-defined strategies automatically. These findings support recent research highlighting the critical role of digitalization in supply chain resilience [35].

V. Conclusion and Implications for the Forwarding Industry

5.1. Conclusion

This study provides the freight forwarding industry with a robust simulation framework to quantify disruption impacts and test mitigation strategies from their unique operational and financial perspective. The findings confirm that a single-strategy approach is inadequate for managing complex disruptions. Resilience is instead a strategic capability built on a portfolio of tactics, informed by careful client segmentation and enabled by pre-emptive planning and digital tool implementation.

The research makes several important contributions to both theory and practice. First, it demonstrates the value of hybrid simulation modeling for capturing the complex interplay between physical logistics processes and strategic decision-making in freight forwarding. Second, it provides empirical evidence of the non-linear nature of disruption impacts, showing that costs escalate more rapidly than time delays due to compounding penalty effects. Third, it offers a structured framework for evaluating mitigation strategies that accounts for both operational and financial outcomes.

Perhaps most importantly, this study highlights the critical role of strategic preparation in building supply chain resilience. The significant performance differences between rapid and delayed responses to disruptions underscore that resilience is not merely about having contingency plans, but about having the capabilities to execute them effectively when disruptions occur. This requires both technological capabilities (visibility platforms, decision support systems) and organizational capabilities (trained staff, clear protocols, client communication frameworks).

5.2. Practical Implications for Forwarders

The research suggests several actionable implications for forwarding firms:

- **Develop Strategy Portfolios:** Move beyond ad-hoc responses by using simulation to pre-test and develop a structured playbook of mitigation strategies for various disruption scenarios. This should include clear decision trees and activation criteria for different strategies.
- **Implement Client Segmentation:** Develop systematic approaches to align mitigation tactics with the value and requirements of specific client contracts, potentially including tiered service offerings with appropriate pricing structures.
- **Invest in Predictive Tools:** Leverage simulation and digital twin technology as a core strategic planning function rather than merely operational tools, positioning this capability as a competitive advantage in the marketplace.
- **Enhance Client Communication:** Use data-driven insights from models like this to set realistic expectations and communicate proactively during disruptions, potentially including visualizations of alternative routing strategies and expected outcomes.

5.3. Limitations and Future Research

While this study provides important insights, several limitations suggest directions for future research. The model assumes rational decision-making based on predefined rules; future work could incorporate more complex, AI-driven decision logic for the FreightForwarderAgent (e.g., reinforcement learning to maximize profit across a mixed cargo portfolio). Additionally, the current model focuses on ocean freight; future extensions could incorporate air freight alternatives and multi-modal complexities. Further research could also explore the dynamics of carrier negotiation and contract flexibility in greater depth, as these factors significantly influence strategy implementation.

Another promising direction for future research would be to expand the model to include environmental sustainability metrics, allowing forwarders to evaluate the carbon footprint implications of different disruption mitigation strategies. This would align with growing client demands for sustainable logistics solutions and regulatory pressures on supply chain emissions.

Finally, future work could explore the potential for collaborative disruption response among multiple forwarders, examining whether coordinated actions could lead to better outcomes for all participants through resource sharing and information exchange.

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