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Evaluating Disruption Management Strategies for Freight Logistics in Oman: A Simulation Modeling Approach

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ABSTRACT

Objective: The logistics and transportation networks in the GCC, particularly in Oman, face unique problems due to the region's geographical complexity, the value of transported goods, and the significance of timely deliveries. Operating in a highly competitive environment, businesses in this industry are compelled to reduce waste, save unnecessary expenditures, and maintain consistent delivery standards while dealing with disruptions that may severely disrupt operations.

Methodology: Our research aims to apply scenario planning-based simulation modelling to examine the effects of disruptions on freight logistics and transportation performance in Oman, with two goals in mind: first, to assess the financial and operational consequences of disruptions, and second, to devise and evaluate proactive and reactive measures aimed at maintaining good service levels to avoid supply shortages. Disruptions in freight logistics and transportation have profound consequences, prompting a deliberate shift to create resilient and flexible networks.

Results: Our findings highlight the effectiveness of activating backup transportation routes in reducing expanded disruptions, while laterally enabling transshipment appears as a viable approach for smaller-scale, short-term disruptions, although with a marginal cost increase.

Conclusion: By implementing these tactics, Oman's logistics and transportation industries can successfully mitigate disruptions in freight logistics and maintain the smooth flow of commodities throughout the region. Additionally, policy-level support for digital transformation and infrastructure development is essential for enabling long-term logistics competitiveness.

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Introduction

Freight logistics systems play a critical role in maintaining supply chain continuity, economic stability, and customer service performance. However, increasing operational complexity, fluctuating market demand, transportation interruptions, supplier shortages, and unexpected facility closures have significantly increased the vulnerability of logistics networks worldwide. Traditional logistics systems often lack the flexibility and responsiveness required to effectively manage such disruptions, particularly in rapidly changing and uncertain business environments. As a result, disruption management and supply chain resilience have become major priorities for logistics organizations seeking to maintain operational continuity and competitive advantage.

Recent global disruptions, including the COVID-19 pandemic, geopolitical conflicts, and transportation infrastructure constraints, have further emphasized the importance of resilient logistics operations. These disruptions have exposed critical weaknesses in freight transportation systems, including limited visibility, inefficient routing structures, workforce shortages, inventory imbalances, and poor coordination among supply chain stakeholders. Consequently, logistics organizations are increasingly adopting simulation-based planning approaches to evaluate disruption scenarios, improve operational preparedness, and support strategic decision-making under uncertainty.

Simulation modelling has emerged as an effective tool for evaluating supply chain behavior under dynamic operating conditions. Simulation-based logistics analysis enables organizations to examine transportation flows, inventory movements, service performance, and disruption-response mechanisms without interrupting real operational activities. In particular, logistics simulation platforms such as AnyLogistix provide capabilities for network design, transportation optimization, inventory analysis, and disruption scenario evaluation. Previous studies have demonstrated the importance of simulation-driven approaches for improving supply chain resilience, transportation planning, and logistics performance during disruption events. However, existing research has primarily focused on conceptual resilience frameworks or generalized supply chain environments, while limited attention has been given to freight logistics systems within the Gulf Cooperation Council (GCC) region, particularly Oman.

Despite the strategic importance of Oman as a regional logistics hub, limited research has investigated disruption management strategies within Omani freight logistics operations using simulation-based approaches. Furthermore, existing studies often emphasize theoretical resilience concepts without providing practical operational evaluation of disruption mitigation strategies under realistic logistics conditions. This creates a significant research gap regarding the application of scenario-based logistics simulation for evaluating operational resilience, transportation efficiency, and disruption recovery capability in the freight logistics sector.

To address this gap, the present study develops a simulation-based digital representation of a freight logistics network using AnyLogistix software and evaluates multiple disruption and mitigation scenarios affecting transportation and logistics operations. The study focuses on four major disruption categories, including supplier shortages, workforce unavailability, facility closures, and demand fluctuations. Corresponding mitigation strategies, including multimodal transportation planning, contingency routing, collaborative logistics operations, and supplier coordination mechanisms, are integrated into the simulation environment to assess their impact on operational resilience and logistics performance.

The study adopts a case-based simulation methodology using operational insights obtained from Oman's freight logistics sector. Primary data were collected through semi-structured interviews with logistics professionals, operational document analysis, and field observations conducted within the case organization. The collected information was subsequently triangulated and incorporated into the simulation model to improve operational realism and analytical reliability.

The findings of this study contribute to the growing body of knowledge on supply chain disruption management and logistics resilience in several ways. First, the study provides a scenario-based simulation framework for evaluating disruption impacts and mitigation effectiveness within freight logistics systems. Second, it offers practical operational insights regarding transportation efficiency, inventory performance, and fulfillment reliability under disruption conditions. Third, the study contributes context-specific evidence from Oman's freight logistics sector, where limited simulation-based resilience research currently exists. Finally, the study provides actionable managerial implications for logistics organizations seeking to improve operational continuity, transportation flexibility, and supply chain resilience in uncertain business environments.

Table 1. Network Optimization Methods in Supply Chain and Logistics

	Methods	Research Area Targeted	Citation
Mathematical Modelling	Heuristic and Neural Network Optimization (If any)	Hamburg Harbor Car Terminal	(Becker et al., 2016)
	Integrated Optimization	Transportation and Logistics Optimization for Carbon Emission Reduction	(L. Li & Zhang, 2020)
	A multi-stage model	Fresh fruit supply chains	(Trivedi et al., 2021)
	Integrating mathematical modeling techniques	Agriculture, procurement organizations, and enterprises of the food industry system.	(Mokhnenko et al., 2020)
	Mathematical modeling and optimization	Supply Chain Management (SCM) and Outsourcing.	((Alkahtani, 2022)
Simulation Modelling	Virtual Digital Twin	Renewable energy systems (RESs), Zero Energy District (ZED), port	((Agostinelli et al., 2022)

		energy efficiency, and digital twin (DT) modeling.	
	Logistics 4.0	Food logistics management within the context of Industry 4.0.	(Jagtap et al., 2020)
	Agent-Based Model (AMB).	Optimizing freight transport and logistics operations, specifically targeting inbound logistics for a company south Italy.	(Calabrò et al., 2023)
	Genetic Algorithm With Adoptive Simulated Annealing Mutation (GAASAM)	Provide efficient, environmentally friendly distribution solutions for fresh food logistics, reducing costs and enhancing social responsibility.	(D. Li et al., 2020)
	Value Stream Mapping (VSM), Gap and Process Analysis, Validation and Improvement, Area Definition and Imitation Modelling.	Agri-food logistics optimization.	(Vostriakova et al., 2021)
	ε-constraint method, Strength Pareto Evolutionary Algorithm II (SPEA-II), Non-dominated Sorting Genetic Algorithm II (NSGA-II), Multi-Objective Grey Wolf Optimizer (MOGWO), and the Multi-Objective Invasive Weed Optimization algorithm (MOIWO)	Healthcare Supply Chain Management	(Shirazi et al., 2021)
	Machine learning and neural network technology.	Supply chain Risk management	(Han & Zhang, 2021)
Other Modelling Approaches	Structural Equation Modelling (SEM)	Optimization of urban transport systems, specifically focusing on paratransit services in Metro Manila	(Tiglao et al., 2020)
	Multi-Criteria Decision Analysis (MCDA)	Optimizing vehicle-route selection and enhancing urban logistical planning, particularly in smart cities	(M.-Y. Wu et al., 2022)

The reviewed literature demonstrates extensive use of optimization, simulation, and resilience-oriented approaches in supply chain and logistics management. Previous studies have investigated disruption management, transportation planning, inventory optimization, and digital logistics systems using various analytical and simulation-based methodologies. However, several important research gaps remain evident.

First, limited disruption-focused simulation studies have examined freight logistics operations within Gulf Cooperation Council (GCC) countries, particularly Oman. Second, existing studies frequently emphasize conceptual resilience frameworks without integrating practical disruption-mitigation scenario evaluation under realistic operational conditions. Third, many previous studies focus on generalized supply chain environments rather than freight-specific logistics systems involving transportation efficiency, vehicle utilization, and fulfillment performance analysis.

Furthermore, while digital logistics and simulation-based approaches have gained increasing attention in recent years, limited research has combined operational disruption analysis, mitigation strategy evaluation, and resilience-oriented logistics performance assessment within a unified simulation framework. Therefore, this study aims to address these gaps by developing a scenario-based simulation framework for evaluating disruption management strategies within Oman's freight logistics sector.

Literature Background

Recent studies in supply chain management and logistics have increasingly emphasized the role of resilience, digital transformation, sustainability, and simulation-based decision-making under disruption conditions. The growing complexity of global logistics operations, combined with uncertainties arising from geopolitical tensions, pandemics, operational risks, and environmental concerns, has motivated researchers to develop more adaptive and technology-driven supply chain frameworks.

A recent bibliometric study by Arash Ghadami and colleagues systematically examined the evolution of artificial intelligence applications in supply chain management using 805 Scopus-indexed publications between 1996 and 2025. Their findings identified resilience, sustainability, digital twins, and machine learning as emerging thematic clusters shaping future supply chain research. The study highlighted the increasing importance of AI-enabled resilience planning and emphasized the need for improved technical integration and evaluation frameworks across logistics sectors. However, the authors noted that most existing studies remain descriptive and lack operational implementation frameworks for disruption-oriented logistics environments.

In the context of resilient supply chain network design, Farahnaz Rahmani Meybodi et al. proposed a resilient three-level intertwined supply network model under disruption and uncertainty conditions in the tile and ceramics industry. Their study employed fuzzy chance-constrained programming and multi-objective optimization to improve both profitability and resilience. The findings demonstrated that capacity development and supplier diversification can significantly reduce operational risk under uncertain conditions. Nevertheless, the study primarily focused on mathematical optimization and did not evaluate dynamic operational behavior through simulation-based logistics analysis.

Similarly, Maryam Bahadoran and colleagues designed a resilient closed-loop supply chain network under operational risk and disruption conditions using the Mulvey robust optimization approach. Their research emphasized the importance of scenario-based modelling for improving supply chain robustness in food industry operations. The study confirmed that resilient network design can reduce operational disruptions and improve system stability. However, the framework mainly concentrated on optimization modelling and lacked practical transportation-network simulation and operational logistics evaluation.

Digital transformation and Industry 4.0 integration have also gained significant attention in recent years. Mohammad Saeed Mozafari Mehr and Mohammad Taghi Taghavifard investigated digital transformation in Iran Khodro Company using a grounded theory and partial least squares approach. Their study identified digital infrastructure, leadership, human resources, and digital strategy as critical enablers of digital transformation within industrial organizations. Although the study contributes valuable insights regarding organizational readiness for Industry 4.0 adoption, its focus was primarily managerial and conceptual rather than operational logistics, resilience, and disruption management.

In humanitarian logistics research, Seyed Pendar Toufighi et al. developed a relief logistics network design model for facility location and flow allocation under environmental considerations. Using mixed-integer linear programming, the study optimized casualty transfer operations under earthquake scenarios in Tehran. The findings demonstrated the importance of pre-disaster logistics planning and capacity allocation in improving emergency response efficiency. While the study contributes significantly to resilient humanitarian logistics design, its focus differs from commercial freight logistics disruption management and transportation performance optimization.

Collectively, the reviewed studies demonstrate growing scholarly attention toward resilient supply chain design, digital transformation, sustainability, and disruption management. However, three major research gaps remain evident. First, limited studies have examined freight logistics disruption management using simulation-based operational analysis within GCC countries, particularly Oman. Second, many existing studies rely primarily on optimization or conceptual modelling approaches without integrating practical transportation-network simulation and dynamic KPI evaluation. Third, there remains limited research combining disruption scenario analysis, mitigation strategy evaluation, and logistics resilience assessment within a unified simulation-driven decision-support framework.

Therefore, the present study contributes to the literature by developing a scenario-based freight logistics simulation framework using AnyLogistix to evaluate disruption impacts and mitigation strategies within Oman’s logistics sector. The study further extends existing resilience-oriented research by integrating operational KPIs, transportation efficiency analysis, and disruption-response evaluation within a practical freight logistics environment.

Materials and Methods

Research Methodology

This study adopted a simulation-based research methodology to evaluate disruption management strategies within Oman's freight logistics sector. The proposed framework integrates qualitative data collection, operational analysis, disruption scenario modelling, and comparative performance evaluation using the AnyLogistix simulation environment. The overall methodological process consisted of nine sequential stages, as illustrated in Figure 1.

Step 1: Problem Identification

The first stage focused on identifying the major operational disruptions affecting freight logistics systems in Oman. Particular attention was given to transportation inefficiencies, supplier shortages, workforce limitations, terminal closures, and demand fluctuations that negatively influence logistics performance and supply chain resilience. The problem identification phase was supported through preliminary discussions with logistics professionals and an extensive review of the supply chain disruption and resilience literature.

Step 2: Data Collection

To ensure realistic modelling of the logistics network, primary operational data were collected from the case company, Asyad Group, which represents one of the leading logistics organizations in Oman. Data collection was conducted using multiple sources to enhance reliability and contextual understanding. First, semi-structured interviews were conducted with logistics managers, supply chain engineers, and operational personnel involved in transportation planning and warehouse management. Second, physical observations were performed at logistics facilities and freight movement locations to understand operational workflows, transportation routing, and shipment handling procedures. Third, company operational documents and logistics records were analyzed, including transportation activities, inventory movements, delivery schedules, and order fulfillment data.

Primary qualitative and operational data were collected through semi-structured interviews, field observations, and company operational document analysis. The interview process involved a total of ten industry professionals from the case organization, including seven logistics managers and three operations engineers directly involved in transportation planning, warehouse operations, and supply chain coordination activities.

Participants were selected using purposive sampling based on their operational expertise and professional experience within the freight logistics sector. All interview participants possessed a minimum of five years of experience in logistics operations, transportation management, or supply chain planning. This selection criterion ensured that the collected insights reflected practical operational knowledge and disruption management experience.

The interviews were conducted in a semi-structured format to allow flexibility in exploring operational disruptions, transportation challenges, resilience practices, and mitigation strategies within the logistics network. Each interview session lasted approximately 45–60 minutes and focused on identifying major disruption sources, operational vulnerabilities, transportation bottlenecks, inventory management issues, and resilience improvement opportunities.

In addition to interviews, physical observations were conducted at logistics facilities and freight movement locations to better understand transportation flows, shipment handling procedures, routing structures, and warehouse operations. Company operational records and logistics performance reports were also reviewed to support model development and scenario configuration.

The collected qualitative information was analyzed using thematic analysis and manual coding techniques. Recurring operational themes, disruption patterns, and mitigation practices were identified and subsequently incorporated into the simulation model development process. Finally, triangulation was performed by comparing interview insights, observational findings, and operational documentation to improve data reliability and reduce potential analytical bias.

Step 3: Data Triangulation

After data collection, a triangulation process was conducted to improve data validity and reduce potential bias. Information gathered from interviews, field observations, and company operational records was systematically compared and cross-validated. This process enabled the identification of consistent operational patterns, disruption sources, and logistics performance indicators while ensuring that the simulation model accurately reflected the real operational environment of the freight logistics system.

Step 4: Supply Chain Modelling in AnyLogistix

The validated operational data were subsequently transformed into a simulation-based digital representation of the freight logistics network using AnyLogistix software. The supply chain structure was designed to represent the primary logistics entities, including suppliers, distribution centers (DCs), transportation routes, and customer zones. Transportation flows, inventory policies, delivery schedules, and routing structures were configured within the simulation environment to reproduce the operational characteristics of the real freight logistics network.

Step 5: Disruption Scenario Design

Following the construction of the simulation model, disruption scenarios were developed to evaluate supply chain vulnerability under uncertain operating conditions. Four major disruption categories were identified and modelled within the system: supplier shortage (D1), shortage of skilled logistics personnel (D2), unexpected industry or terminal closure (D3), and demand fluctuation (D4). Each disruption was independently simulated to assess its direct impact on logistics performance and operational continuity.

Step 6: Mitigation Strategy Integration

To evaluate supply chain resilience and recovery capability, corresponding mitigation strategies were incorporated into the simulation model. These included multimodal transportation development (S1), collaboration with regional logistics partners (S2), contingency routing strategies (S3), and supplier/customer agreement mechanisms (S4). The mitigation strategies were paired with their associated disruption scenarios to examine the effectiveness of proactive and reactive response mechanisms in reducing operational risk.

Step 7: Simulation Execution

The simulation experiments were executed using the AnyLogistix platform under multiple operational scenarios. To improve the robustness and reliability of the results, each scenario was simulated through ten independent experimental runs using different random seed values. This repeated execution process reduced stochastic bias and enabled more stable estimation of supply chain performance under uncertain operational conditions.

Step 8: KPI Evaluation

The operational performance of each scenario was evaluated using four key performance indicators (KPIs): on-time fulfillment rate, transportation cost, vehicle capacity utilization, and inventory carrying cost. These KPIs were selected because they comprehensively represent customer service performance, transportation efficiency, resource utilization, and inventory management effectiveness within freight logistics operations. For each KPI, statistical measures including minimum, maximum, mean, and standard deviation values were calculated to assess both operational efficiency and result stability.

Step 9: Comparative Analysis

Finally, a comparative analysis was conducted between disruption-only scenarios and mitigation-enabled scenarios to evaluate the effectiveness of the proposed resilience strategies. The analysis focused on identifying operational improvements, cost reductions, service-level recovery, and overall supply chain stability under different disruption conditions. The comparative assessment enabled the identification of the most effective disruption management strategies for enhancing resilience and operational sustainability within Oman's freight logistics sector.

The proposed methodology provides a structured framework for integrating disruption analysis, simulation modelling, and resilience evaluation into freight logistics decision-making. Furthermore, the methodology offers practical applicability for logistics managers and policymakers seeking to improve operational continuity and supply chain robustness under uncertain business environments. The flowchart 1 illustrates these steps.

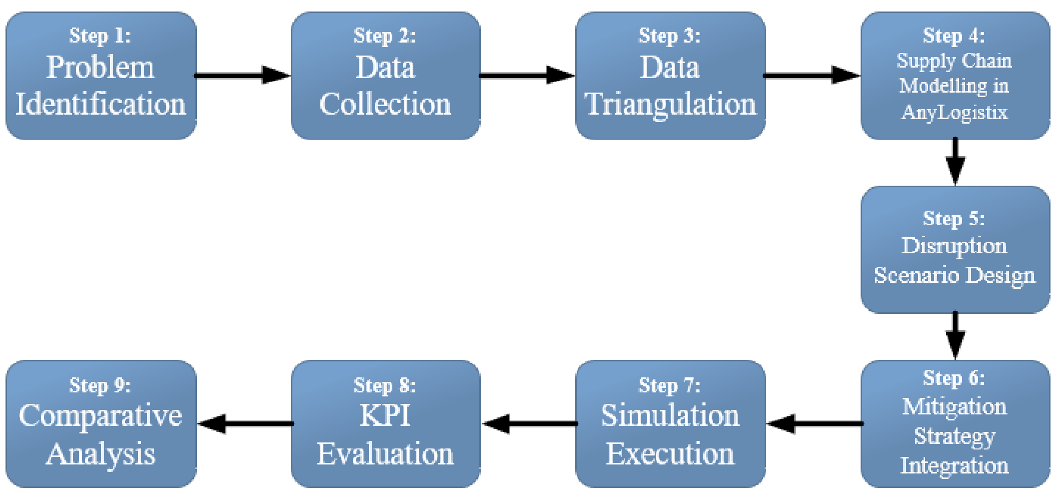

Figure 2. How the ASYAD framework Works

Case Company Description

Oman's government is currently working to boost the logistics industry by forming the ASYAD group, which administers and regulates several logistics companies and organizations in Oman. Therefore, Asyad Group has been at the forefront of revolutionizing Oman's logistics industry. According to Hamed Al-Wahaibi, 2019) ASYAD has collaborated with MTIC and the Implementation Support Unit to develop the Oman logistics sector, making it a top hub and improving the logistics performance index. Asyad's commitment to advanced technologies has increased the sector's impact on Oman's GDP, reaching 4% in 2020 (ASYAD, 2021)

According Times of Oman, (2021), Asyad operates over a commerce zone, two free zones, and three deep ports. Oman is connected to 86 commercial ports across 40 countries by its varied fleet of 60 vessels, creating a robust worldwide trading network. The country's free zones, including as Khazaen Economic City, Salalah, and Sohar, have drawn foreign direct investment and SMEs, which have strengthened the logistics sector. Over OMR 2 billion worth of developments have come from these zones, and another OMR 450 million is currently under construction.

Asyad Group provides a flexible logistics solution for local and international businesses in the Middle East and Africa market, consisting of four businesses: Oman Rail Company, Oman Shipping Company, Oman Post Company, and Oman Dry Dock Company. Complete transportation, freight forwarding, warehousing, ship maintenance, and rail network solutions are all provided by Asyad. To satisfy a variety of customer requirements, it also offers end-to-end services, e-commerce solutions, and smart logistics.

In terms of facility location planning, Asyad faces several Challenges as mentioned below.

Geopolitical risks - operating in regions like the Red Sea requires balancing growth strategies with potential risks, especially when considering acquisition in ports and logistics hubs across East Africa, the Far East, and India (Benny, 2024).

Technological Risk - the logistics sector is rapidly evolving with advancements in technology. Asyad has been proactive in adopting cutting-edge technologies to create a state-of-the-art logistics infrastructure, which is crucial for effective facility location planning (ASYAD | Building a Legacy, 2021).

Sustainability considerations - the global shift toward green energy and sustainable practices necessitates that Asyad incorporate environmental considerations into its facility planning to meet international standards and regulations.

Network route optimization for the company involves collecting and analyzing data on transportation costs, delivery times, distance, fuel consumption, and traffic patterns. It involves using algorithms to plan and design cost-effective routes, minimizing empty truck loads, and balancing delivery frequency with capacity. Fleet allocation is based on demand load capacity, and real-time monitoring is used to adjust routes dynamically. Network route optimization benefits from cost efficiency, improved delivery times, sustainability, and increased customer satisfaction.

Real-Time Scenario on How the Asyad framework works

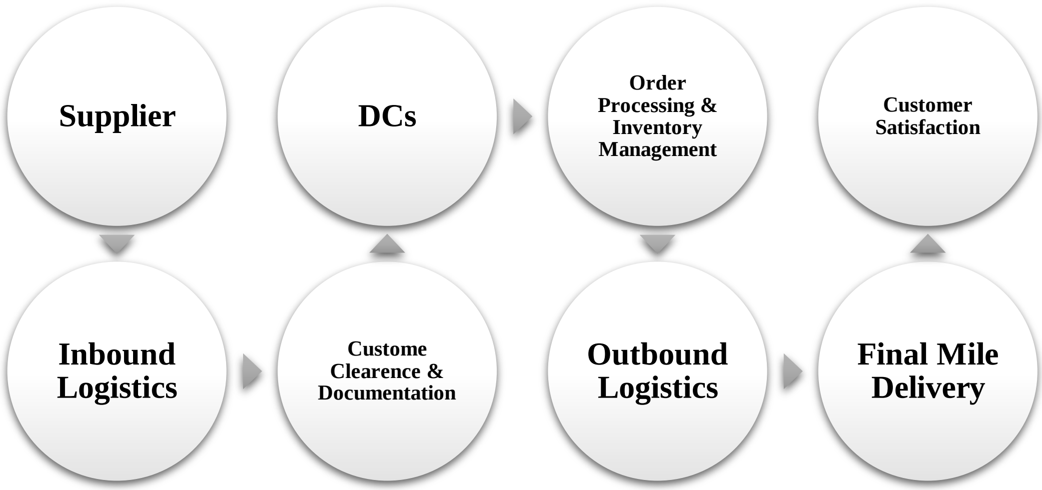

Figure 2. How the ASYAD framework Works

Asyad collaborates with local and international suppliers for raw materials, components, and finished goods. It handles inbound logistics (sea, air, road, rail), customs clearance and documentation, distribution centers, order processing, inventory management, outbound logistics (transport to customers), and final mile delivery (B2B, B2C, retail). The company uses Oman's major ports and transportation hubs for goods arrival, and it distribution centers store, handle, and sort products. Order processing and inventory management ensure efficient and timely delivery. Asyad extensive distribution network reaches businesses, retailers, and direct customers. Real-time tracking, data analytics, and customer feedback improve logistics efficiency and ensure seamless operations.

The supply chain-related data was collected and organized to understand the freight logistics working setup. The authors approached the supply chain manager and logistics engineer of the company and acquired data on supply chain operations, which was later validated by cross-checking with the company documents and relevant logistics records. Supply chain KPIs. The assessment of the supply chain performances under diverse scenarios involves the utilization of the KPIs listed and described in Table 2 below.

Table 2. Key Performance Indicators for evaluating the different scenarios

Key Performance Indicators (KPIs)	Additional Information
$\text{On}-\text{Time Fulfillment Rate }(\%) = \dfrac{\text{Orders Delivered On}-\text{Time}}{\text{Total Orders Delivered}} \times 100\%$	It measures customer order delivery within the promised time frame, indicating supply chain efficiency and customer satisfaction. High on-time fulfillment improves customer experience and revenue.
$\text{Transportation Cost per Km} = \dfrac{\text{Total Transportation Cost}}{\text{Total Dictance Travelled (km)}}$	It represents the expense incurred to move goods across the supply chain. High transportation costs can impact profitability and efficiency.
$\text{Vehicle Capacity Utilization }(\%) = \dfrac{\text{Volume Shipped}}{\text{Vehicle Capacity}} \times 100\%$	It measures vehicle capacity utilization during transportation, focusing on high utilization to reduce costs and improve resource efficiency.
$\text{Inventory Carriying Cost} = \text{Holding Cost per Unit } \times \text{Average Inventory}$	It is the total cost of holding inventory over a specific period. High cost can tie up cash flow and lower profitability.

The KPIs provide a comprehensive view of supply chain performance, ensuring customer satisfaction, evaluating logistics efficiency, maximizing transportation performance, and assessing the company's financial condition.

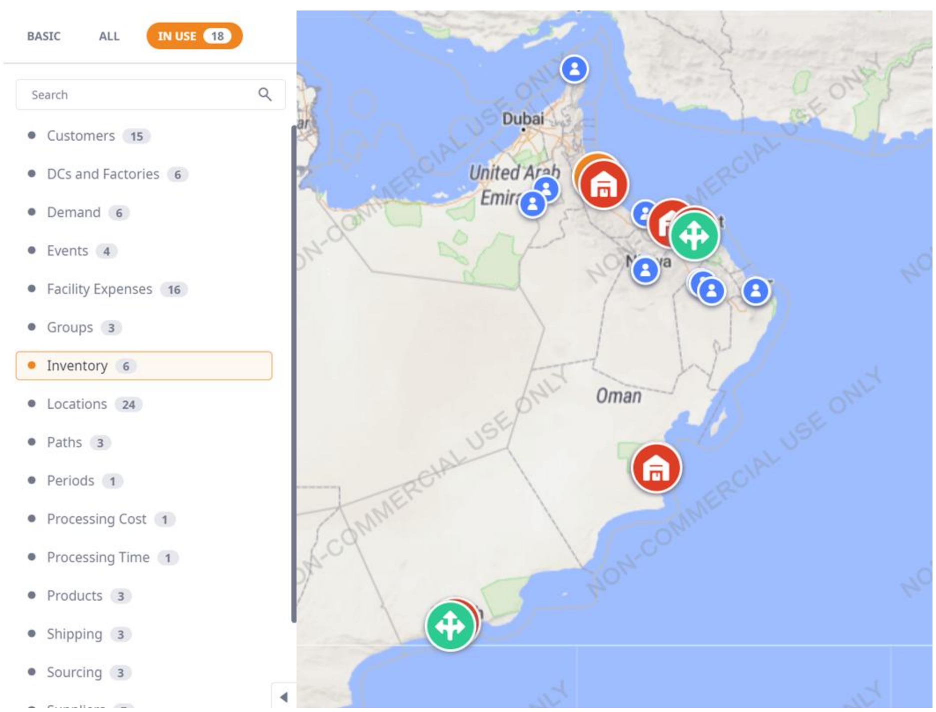

Figure 3. Input Tables and Graphical View the Supply Chain Digital Twin.

The Digital Twin of the Freight Model

The supply chain model for digitalization is implemented after completing previous phases. The real supply chain is reproduced using the software tool, which accurately replicates the supply chain's operating mechanisms, such as product demand, warehouse policies, and freight methods, as shown in Figure 3.

The framework proposed targets the freight logistics supply chain of Oman, focusing more on the resilience and sustainability factors. The objective of this study is to improve their risk assessment and evaluations via mitigation plans during disruptions. After supply chain data collection and footprint understanding, freight transportation-related KPIs were assessed under various scenarios. Solutions were suggested from operational, tactical, and strategic perspectives from the supply-side (SuS), middle-side (MiS), or demand-side (DeS).

Later, this operational data is transformed and modeled, combining various scenarios for multiple simulation runs. To demonstrate the effectiveness of the proposed methodology, we address a case study in the freight logistics sector, which considers a supply chain characterized by 4 main levels: suppliers, distribution center (DC), customers, and retailers. It is important to underline that the supplier’s customers are wholesalers.

The disruptions and mitigation strategies presented in Tables 3 and 4 were identified through a triangulated process involving literature review, semi-structured interviews with logistics experts at Asyad Group, operational document analysis, and field observations. The identified factors were then validated through expert discussions to ensure their relevance to the Omani freight logistics context.

Table 3. Main Disruptions (D) considered

ID	Type	Description	Main effect
D1	TnS	Lack of advanced infrastructure in certain regions, shortage of suppliers	Inefficient routing, increased transportation costs, and delays in delivery schedules negatively impact service levels and customer satisfaction.
D2	TnS	Shortage of skilled logistics personnel	Challenges in optimizing transportation networks, leading to inefficiencies in freight movement and delays in strategic planning.
D3	MiS	Unexpected industry or terminal closures	Disruptions in freight movement, increased detention fees, and reduced supply chain resilience.
D4	DeS	Demand fluctuations (i.e., unexpected increase or decrease)	Unforeseen sudden demand can lead to business loss and environmental damage due to delayed product distribution.

Table 4. Main Solutions (S) considered

ID	Type	Description	Main effect
S1	TnS	Development of multimodal transportation infrastructure	Enhances connectivity between regions, reduces transportation costs, and ensures timely deliveries.
S2	SuS/TnS	Collaboration with regional logistics partners	Increases capacity and reliability, addressing infrastructure and manpower limitations effectively.
S3	MiS	Implementation of contingency routing strategies	Reduces dependency on key nodes (e.g., ports) and ensures uninterrupted freight flow during closures.
S4	DeS	Agreements with the product suppliers / Agreements with spot customers	Agreements with other producers and spot customers help meet demand, manage market limitations, and ensure the product remains available during sudden peaks.

Now it is necessary to define scenarios, based on disruptions and solutions identified previously. There are no well-defined rules for defining scenarios, which can be built by combining (even all) disruptions and solutions. However, it is good practice to always define one or more scenarios in which there are disruptions and no solutions implemented; this makes it possible to evaluate the current level of resilience of the supply chain, thus answering the following question: how much is the supply chain currently "vulnerable" to the disruptions identified? Table 5 shows the list of identified scenarios.

Results

As can be seen in Table 5, the first 4 scenarios represent the occurrence of the 4 types of identified disruptions, separately. The next 4 scenarios (i.e., 5–8) aim to understand how effective each identified solution is in dealing with each identified disruption. The scenarios were designed on AnyLogistix through the "Events" table, which allows you to simulate the occurrence of events and associate a probability level with each of them. Figure. 3 and 4 show an extract from this table with reference to Scenario 4, which considers the closure of the DC in some time periods as a disruption.

The scenario structure was designed to evaluate both disruption vulnerability and mitigation effectiveness. Scenarios 1–4 individually simulate the occurrence of a single disruption to isolate its operational impact. Scenarios 5–8 combine each disruption with its corresponding mitigation strategy to assess the effectiveness of the proposed resilience measure. This one-to-one scenario pairing enables controlled comparative analysis between disrupted and mitigated operational conditions.

Table 5. Scenarios identified and Example Events Table for Scenario 4

Scenarios	Disruptions				Solutions			
	D1	D2	D3	D4	S1	S2	S3	S4
Scenario 0								
Scenario 1	□							
Scenario 2		□						
Scenario 3			□					
Scenario 4				□				
Scenario 5	□				□			
Scenario 6		□				□		
Scenario 7			□				□	
Scenario 8				□				□

Event Time Schedule		
Event	Date	Day
Event 3	1/22/25 2.36 PM	22
Event 4	3/31/25 AM	90
Event 2	4/5/25 2:21 AM	95
Event	9/24/25 2.34 PM	267

Model Validation

To ensure the reliability and robustness of the simulation results, multiple validation procedures were conducted throughout the model development and experimental phases. Since simulation-based logistics studies are highly dependent on the accuracy of operational assumptions, network configuration, and scenario behavior, the validation process focused on improving model credibility and reducing potential analytical bias.

First, face validation was conducted through consultation with logistics professionals and operational experts from the case organization. The structure of the logistics network, transportation flows, disruption definitions, and mitigation strategies were reviewed by domain experts to confirm that the simulation model adequately represented the real operational characteristics of the freight logistics system. Expert feedback was also used to refine routing logic, inventory assumptions, and disruption-response relationships within the simulation environment.

Second, historical validation was performed by comparing the baseline simulation outputs with available operational performance records obtained from the company. Key operational indicators such as transportation activity, order fulfillment behavior, and inventory movement patterns demonstrated acceptable consistency with historical logistics operations. This comparison increased confidence that the simulation model reasonably reflects the operational behavior of the real freight logistics network under normal conditions.

To reduce stochastic variability and improve result stability, each simulation scenario was executed through ten independent replications using different random seed values. The repeated simulation runs enabled more reliable estimation of operational performance indicators and minimized the influence of random fluctuations on the final results. Average KPI values were subsequently used for comparative scenario evaluation.

Sensitivity considerations were also incorporated to assess the responsiveness of the simulation outputs under varying operational conditions. The analysis indicated that disruption severity, transportation delays, workforce shortages, and inventory availability significantly influence fulfillment performance, transportation efficiency, and operational cost behavior. Despite variations in operational parameters, the overall ranking and comparative trends among the scenarios remained relatively stable, supporting the robustness of the simulation findings.

Overall, the validation procedures confirmed that the proposed simulation-based logistics model provides a sufficiently reliable framework for evaluating disruption management strategies and operational resilience within Oman's freight logistics sector.

The events are essential for simulating real-world logistics scenarios by triggering specific actions at scheduled times. These events can represent demand fluctuations, supply chain disruptions, and transportation delays. The event table outlines the potential impact of events on logistics simulation. Demand fluctuation can trigger sudden changes in the supply chain, testing the adaptability of the supply chain. For the 'event', likely a major end-of-year shift, such as peak season demand or capacity expansion. Event 2 may indicate a logistics optimization update or warehouse restocking. Event 3 might represent an early supply chain disruption or demand spick. For event 4, it could be a policy change, a new supplier contract, or a seasonal demand shift.

Table 6. KPI 1: On-Time Fulfillment Rate under Scenarios 1-8

Scenarios	Min	Max	Mean	std-dev
Scenario 1	8,018,689.96	8,400,761.50	8,185,676.32	129,448.02
Scenario 2	8,417,982.35	8,898,493.69	8,674,223.67	152,736.56
Scenario 3	8,023,579.69	8,440,077.77	8,233,413.98	105,089.75
Scenario 4	8,119,486.31	8,533,459.84	8,334,318.73	102,808.91
Scenario 5	8,300,401.73	8,786,073.16	8,525,864.49	139,330.52
Scenario 6	8,035,505.41	8,339,647.16	8,220,743.01	91,833.85
Scenario 7	8,099,874.41	8,434,942.13	8,287,777.82	97,115.89
Scenario 8	8,377,082.34	8,951,692.58	8,633,053.77	174,334.47

Table 7. On-Time Fulfillment Rate for All Scenarios

Scenarios	Orders Delivered On-Time	Total Orders Delivered	On-Time Fulfilment Rate (%)
Scenario 1	950	1000	95%
Scenario 2	870	1200	72.5%
Scenario 3	1480	1500	98.7%
Scenario 4	600	750	80%
Scenario 5	2300	2500	92%
Scenario 6	1150	1400	82.1%
Scenario 7	1900	2000	95%
Scenario 8	500	600	83.3%

Table 8. KPI 2: Transportation Cost under Scenarios 1-8

Scenarios	Min	Max	Mean	std-dev
Scenario 1	8,027,770.84	8,097,766.67	8,048,769.59	30,192.17
Scenario 2	8,029,804.50	8,100,878.90	8,072,449.14	31,932.16
Scenario 3	8,261,955.57	8,359,517.87	8,349,761.64	22,875.56
Scenario 4	8,044,420.08	8,091,649.87	8,068,034.98	21,919.49
Scenario 5	8,359,418.87	8,359,664.67	8,359,615.51	85.12
Scenario 6	7,951,090.74	8,018,167.73	8,004,752.33	23,227.15
Scenario 7	8,360,182.85	8,360,182.85	8,360,182.85	0.00
Scenario 8	7,994,535.52	7,994,535.52	7,994,535.52	0.00

Table 9. Transportation Cost per Km for All Scenarios

Scenarios	Total Transportation Cost ($)	Total Distance Traveled (km)	Transportation Cost ($/km)
Scenario 1	5000	10000	$0.50
Scenario 2	12000	18000	$0.67
Scenario 3	8500	15000	$0.57
Scenario 4	25000	40000	$0.63
Scenario 5	4200	7000	$0.60
Scenario 6	18000	30000	$0.60
Scenario 7	22500	45000	$0.50
Scenario 8	10000	16000	$0.63

Table 10. KPI 3: Vehicle Capacity Utilization under Scenarios 1-8

Scenarios	Min	Max	Mean	std-dev
Scenario 1	8,169,200.27	8,528,465.49	8,313,469.13	108,079.29
Scenario 2	8,088,881.17	8,411,555.89	8,255,027.72	105,613.49
Scenario 3	8,270,995.67	8,790,018.87	8,515,469.19	161,289.07
Scenario 4	8,424,241.06	8,867,118.21	8,636,224.74	138,877.44
Scenario 5	7,937,037.48	8,247,344.01	8,094,857.85	95,070.10
Scenario 6	8,395,935.04	8,817,979.31	8,665,604.34	134,924.82
Scenario 7	8,000,459.45	8,388,580.37	8,209,733.72	106,671.45
Scenario 8	7,924,835.43	8,253,876.49	8,059,541.58	93,571.42

Table 11. Vehicle Capacity Utilization for All Scenarios

Scenarios	Volume Shipped	Vehicle Capacity	Vehicle Capacity Utilization (%)
Scenario 1	45	50	90%
Scenario 2	30	50	60%
Scenario 3	48	50	96%
Scenario 4	25	40	62.5%
Scenario 5	38	45	84.4%
Scenario 6	20	50	40%
Scenario 7	50	50	100%
Scenario 8	35	50	70%

Table 12. KPI 4: Inventory Carrying Cost under Scenarios 1-8

Scenarios	Min	Max	Mean	std-dev
Scenario 1	8,237,803.28	8,558,094.91	8,450,220.91	98,306.78
Scenario 2	8,199,539.12	8,520,299.07	8,340,090.28	95,962.46
Scenario 3	7,964,604.33	8,293,560.54	8,174,162.60	85,047.10
Scenario 4	8,445,381.12	8,947,855.46	8,733,476.85	148,239.84
Scenario 5	8,016,014.94	8,411,555.89	8,218,653.65	120,239.78
Scenario 6	8,047,942.33	8,471,964.00	8,249,598.16	142,145.76
Scenario 7	8,424,084.47	8,931,455.59	8,645,464.90	170,812.45
Scenario 8	8,144,754.20	8,513,869.94	8,315,736.65	120,250.58

Table 13. Inventory Carrying Cost for All Scenarios

Scenarios	Holding Cost per Unit ($)	Average Inventory (units)	Inventory Carrying Cost ($)
Scenario 1	5	1000	$5,000
Scenario 2	8	1500	$20,000
Scenario 3	6	1200	$7,200
Scenario 4	10	3000	$30,000
Scenario 5	4	800	$3,200
Scenario 6	7	1500	$10,500
Scenario 7	9	2200	$19,800
Scenario 8	3	600	$1,800

The simulation model was run 10 times for each scenario to adequately evaluate the reliability of the results obtained. Repeated execution of the model, containing probabilistic parameters, provides a more complete and reliable view of the system's behavior under conditions of uncertainty, helping to make more informed and robust decisions. This re execution was enabled by changing the random seed of the experiment settings in AnyLogistix.

Tables 6, 8, 10, and 12 show the values of the 4 KPIs under the different scenarios. For each KPI, the minimum, maximum, and average value were calculated. Furthermore, in order to provide the reader with as much information as possible about the reliability of the results obtained, the standard deviation (std-dev) is also provided. It is important to mention that AnyLogistix provides some useful indicators directly.

Through scenario 0, the normal functioning of the supply chain was simulated, based on historical data provided by the company. In scenarios 1–4, the following disruptions were separately simulated: (i) shortage of suppliers, the port of Muscat was closed and not supplying the products; (ii) Shortage of skilled logistics personnel; (iii) Unexpected industry or terminal closures; (iv) Demand fluctuations (i.e., unexpected increase or decrease) chosen randomly. The KPIs for on-time delivery, transportation cost, vehicle capacity utilization, and inventory carrying cost are essential for understanding supply chain efficiency and customer satisfaction.

On-time fulfilment rate is the percentage of orders delivered within the promised timeframe, with scenarios ranging from 8,185,676.32 to 8,674,223.67. Scenario 8 shows the highest average, but it also has the highest variability, suggesting inconsistency in delivery times. Lower standard deviation values indicate more stable and predictable delivery performance. Transportation cost ranges from 7,994,535.52 to 8,360,182.85, with scenarios 7 and 8 having zero standard deviation, while scenarios 1, 2, and 4 have slightly higher fluctuations. These scenarios are more cost-efficient and consistent, but they may require further investigation into cost drivers. Vehicle capacity utilization is measured by the mean utilization rate, with scenario 6 performing the best overall. Scenario 5 has the lowest mean utilization, possibly due to underutilization of transport resources. Inventory carrying cost measures the cost of holding inventory over time, with scenario 4 having the highest mean. Scenarios with lower mean values and standard deviation are more cost-effective and stable, while scenario 4 requires better inventory management to control costs.

Overall, all these KPIs provide valuable insight into the performance of different scenarios. Scenarios with higher mean values and lower standard deviation show better reliability and efficiency, while scenarios with higher variability and fluctuating costs may require further optimization strategies.

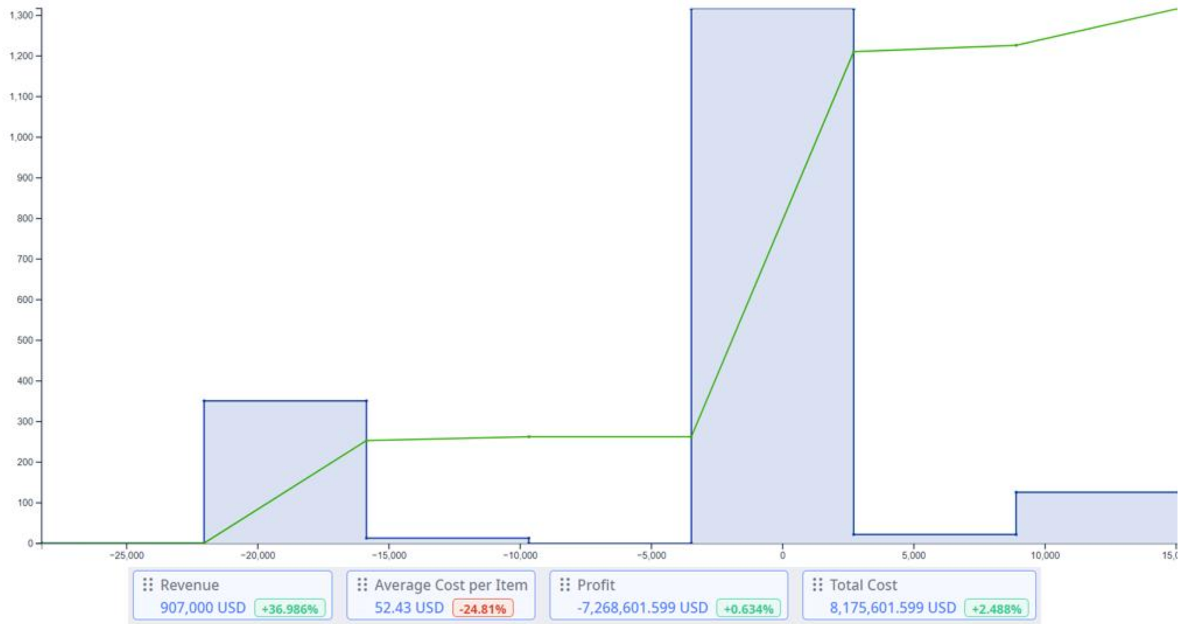

Figure 4. Results on Revenue, Average cost, profit and Total Cost

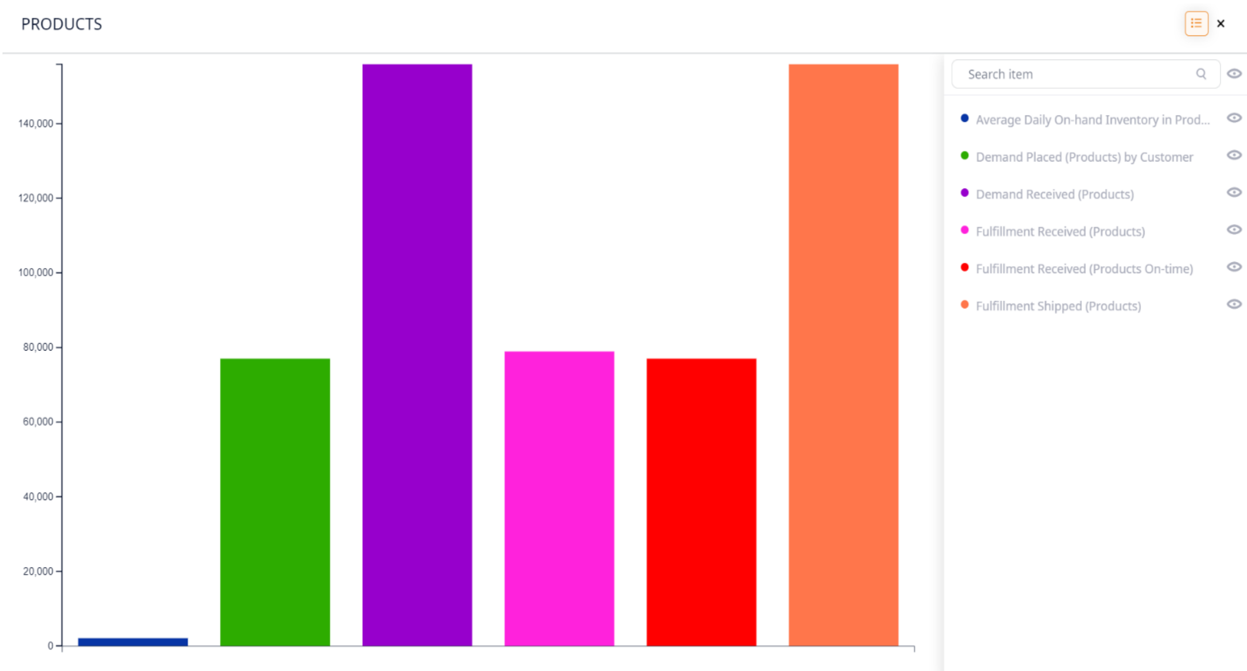

Figure 5. Product Demand, Fulfillment, and Inventory Overview

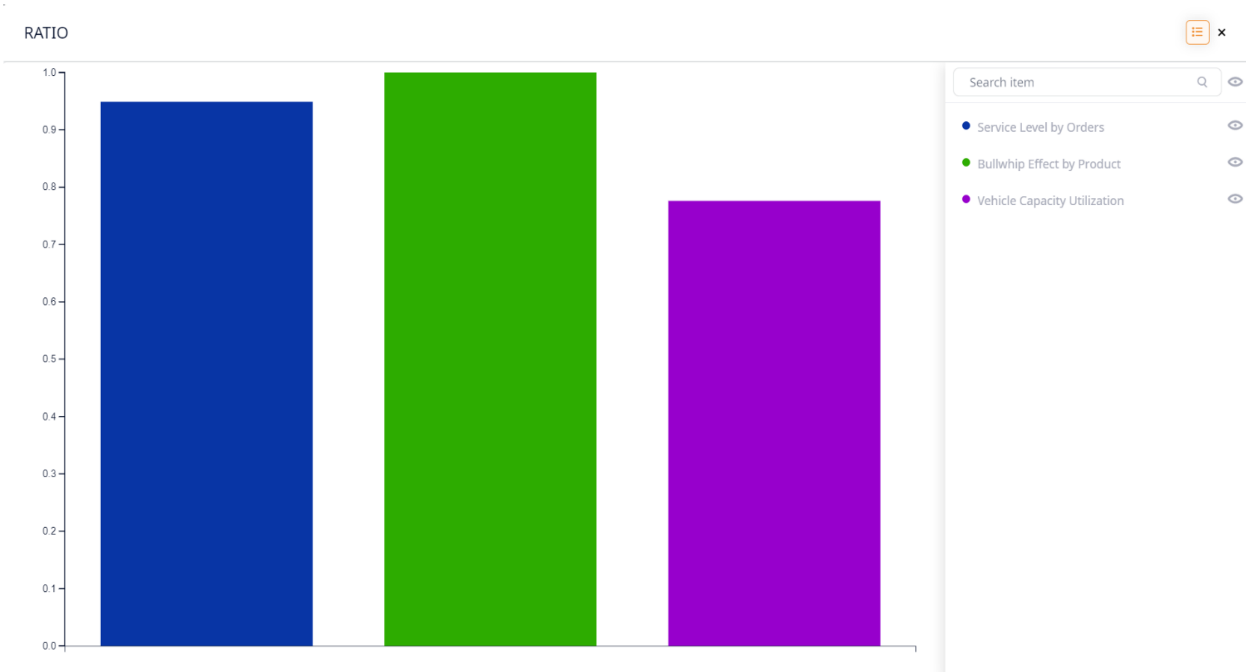

Figure 6. Key Operational Performance Ratio

Discussion

Pathway towards Sustainable Logistics

The logistics industry plays a crucial role in global commerce (Gani, 2017). However, Carli et al., (2020) and (Arkhipov & Maslennikov, 2021) have stated that logistics is transforming into an energy-intensive sector, raising substantial concerns about sustainability at both local and global levels. As a means of minimizing negative environmental impacts associated with energy emissions, (Muñoz-Torres et al., 2018) studied how businesses are increasingly implementing sustainability principles in their logistics operations. Their assertive approach toward the environment has helped them to reap the benefits of an environmentally friendly image, e.g., to gain or retain environmentally conscious consumers, to comply with the sometimes cumbersome and blurry current legislation, and to anticipate necessary changes to cope with future legal environmental standards. This aligns with the findings of (Abbasi & Nilsson, 2016), where sustainability-related initiatives have reduced the negative effects of freight transportation. Mostly, the initial costs potentially pose a challenge for small and medium-sized businesses (SMEs). According to Sibanda et al., 2018), most SMEs have not embraced green logistics activities due to internal barriers such as costs, lack of resources, and knowledge, along with common external barriers like poor infrastructure and roads. Csiszár et al. (2019), argued that in numerous regions, sustainable freight logistics infrastructure is deficient, including insufficient public transportation and electric vehicle charging stations. For instance, a study on implementing electric vehicles on a commercial note (Al-Hanahi et al., 2021) found four main challenges for public charging stations: daily operational schedules of commercial vehicles, charging cost of commercial vehicles at public charging stations, utilization rates of public charging infrastructure, and Stability limits of grid systems, especially during peak residential load. On the other hand,(İmre et al., 2021) studied the Resistance to Change to New Sustainable Technologies in Freight Logistics in Turkey. They concluded that there was an aversion to new technologies and resistance to change. This Resistance from stakeholders can hinder the adoption of sustainable logistics practices. Nevertheless, researchers have suggested various tools and techniques to achieve sustainable freight logistics (Wei et al., 2019; Bibri et al., 2024). According to (Wei et al., 2019), numerous methods and techniques are employed within the framework of green logistics, especially focusing on freight logistics. This is where DT plays a major role in simulating the current and future scenarios in reducing time, energy, and material, and creating a sustainable logistics network.

Bibri et al., (2024) stated that DT can suggest solutions that contribute significantly to environmental sustainability. To optimize operations to increase productivity and reduce waste, DT simulates manufacturing processes and identifies potential bottlenecks (Li et al.,2022) and inefficiencies in manufacturers to develop sustainable strategies and practices(Groten & Gallego-García, 2021). Additionally, DT contributes optimal resource consumption to enable cost savings through judicious use of materials, energy, and labor (Khanfar et al., 2021). DTs can also capture carbon footprints, conserve resources, and ensure responsible business practices. (Corrado et al., 2022)

Digital twin models and Geographic Information System (GIS), and renewable energy systems integrate IoT sensors, artificial intelligence, and real-time data to enhance energy efficiency. Open-source tools like "Renewables. Ninja" and "RSE Wind Atlas" help evaluate wind and solar power potential. The DT model allows detailed analysis of energy consumption, enabling informed decision-making. Reanalysis data helps assess wind and solar energy potential, contributing to sustainable logistics and supply chain management.

While this study provides valuable insights into disruption management in freight logistics through scenario-based simulation, it does not yet incorporate machine learning-driven predictive components or Net-Zero-specific KPIs. A growing body of research highlights the benefits of such integration and data analytics approach. For example, Sayardoost Tabrizi et al. (2025a) combined machine learning clustering with Network Data Envelopment Analysis (NDEA) to enhance efficiency evaluation of petrochemical supply chains, while Sayardoost Tabrizi et al. (2025b) extended this framework with Dynamic NDEA and circular-economy metrics to strengthen benchmarking and sustainability assessment. More recently, Sayardoost Tabrizi et al. (2025c) introduced deep learning forecasting into DNDEA to predict future input–output relationships, showing how predictive analytics can directly support managerial decision-making. Building on these advances, future research should integrate predictive and prescriptive machine learning models into disruption management simulations, enabling richer scenario diversity, more comprehensive Net-Zero KPIs, and improved decision-support capabilities.

Current Logistics Trends in GCC and Oman

Oman and other Gulf Cooperation Council (GCC) countries are investing significantly in infrastructure development to enhance logistics competitiveness and regional integration. According to Ba-Awain & Daud (2018), Oman has undertaken substantial efforts to strengthen its logistics sector in recent years. In addition, Middle East Logistics (2016) highlights that a major focus across GCC countries has been on improving port infrastructure and land transportation systems.

Government initiatives continue to play a critical role in strengthening logistics capabilities in Oman, particularly through investments in ports, airports, and road and rail infrastructure (Ba-Awain & Daud, 2018). The Sultanate's long-term vision to become a global logistics hub by 2040 further reinforces the strategic importance of the logistics sector (Finance Tribune, 2018). In this context, stakeholders such as Asyad have contributed significantly to the growth and modernization of Oman's logistics ecosystem (Hakro & Ommezzine, 2016).

Infrastructure development has shown steady improvement, with Al Barwani (2016) reporting a 3.4% increase in infrastructure development in 2016 compared to the previous year, alongside continued investment in national rail network development. In parallel, digitalization and automation are increasingly shaping logistics transformation across GCC countries.

Technologies such as IoT, artificial intelligence, blockchain, and data analytics are being progressively adopted; however, their integration into logistics operations remains at an early stage. Rahman et al. (2022) emphasize that Industry 4.0 adoption within GCC logistics sectors is still in a nascent phase, with significant potential for further development.

Table 1 summarizes the methodological approaches employed in prior studies on supply chain and logistics network optimization. The synthesis of these studies highlights the need for more disruption-focused, simulation-based, and region-specific logistics research frameworks.

Conclusion

This study investigated the optimization of a freight logistics network in Oman using an AnyLogistix-based simulation framework. The results demonstrate that supply chain disruptions—such as supplier shortages, workforce limitations, unexpected facility closures, and demand fluctuations—have a significant impact on key performance indicators, including on-time fulfillment rate, transportation cost, vehicle capacity utilization, and inventory carrying cost.

The baseline scenario (Scenario 0) represents normal operational conditions, while Scenarios 1–4 simulate individual disruption events. In contrast, Scenarios 5–8 evaluate the effectiveness of corresponding mitigation strategies. The comparative analysis indicates that contingency routing significantly reduces the operational impact of facility closures, while supplier collaboration mechanisms improve stability under demand fluctuations. Furthermore, multimodal transportation strategies contribute to reduced transportation costs and improved delivery performance.

Overall, the findings confirm that a simulation-based decision-support approach using AnyLogistix enables logistics organizations to evaluate disruption scenarios, assess mitigation effectiveness, and improve transportation network performance under uncertainty. The study therefore, contributes to the growing body of research on scenario-based logistics resilience modelling in freight transportation systems.

From a managerial perspective, the simulation outcomes suggest several actionable strategies for improving logistics resilience and operational efficiency in Oman's freight logistics sector. These include the adoption of digital simulation tools for decision support, development of multimodal and resilient transportation networks, strengthening supplier and logistics partnerships, implementation of contingency routing strategies, enhancement of inventory and demand forecasting systems, workforce training and digital capability development, and reinforcement of sustainability-oriented logistics practices. Additionally, policy-level support for digital transformation and infrastructure development is essential for enabling long-term logistics competitiveness. Finally, integrating green logistics strategies and circular economy principles can further enhance environmental performance and operational sustainability. These recommendations collectively aim to improve supply chain resilience, cost efficiency, and service reliability in an increasingly uncertain and competitive global logistics environment.

Ethical considerations

The authors avoided data fabrication, falsification, and plagiarism, and any form of misconduct.

Author Contributions

All authors contributed equally to the conceptualization of the article and writing of the original and subsequent drafts.

Data Availability Statement

Not applicable.

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Conflict of interest

The authors declare no conflict of interest.

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