



ARTICLE

Strategic Assessment of Sustainable Marine Logistics in Arctic Routes Using Resilient and Agile Supply Chain Theory

Suleiman Ibrahim Mohammad ^{1,2*} , Sultan Alaswad Alenazi ³ , Asokan Vasudevan ^{4,5,6} , Hanan Jadallah ¹ , Badrea Al Oraini ⁷

¹ Electronic Marketing and Social Media, Economic and Administrative Sciences, Zarqa University, P.O. Box 132222, Zarqa 13110, Jordan

² Faculty of Business and Communications, INTI International University, Negeri Sembilan 71800, Malaysia

³ Department of Marketing, College Administration, King Saud University, Riyadh 12372, Saudi Arabia

⁴ Faculty of Business and Communications, INTI International University, Persiaran Perdana BBN Putra Nilai, Nilai 71800, Malaysia

⁵ Faculty of Management, Shinawatra University, 99 Moo 10, Bangtoey, Samkhok, Pathum Thani 12160, Thailand

⁶ Business Department, Wekerle Business School, Jázmin u. 10, 1083 Budapest, Hungary

⁷ Department of Business Administration, College of Business and Economics, Qassim University, Buraidah 51452, Saudi Arabia

ABSTRACT

The rapid transformation of Arctic maritime routes, driven by diminishing sea ice and shifting geopolitical conditions, presents both opportunities and challenges for global shipping. This study develops an integrated optimization framework for sustainable Arctic marine logistics, grounded in Agile Supply Chain Theory (ASCT), to address cost efficiency, environmental sustainability, and operational robustness under climate and policy uncertainty. A Mixed-Integer Linear Programming (MILP) model was employed to optimize vessel routing across Arctic corridors, incorporating Energy Efficiency Operational Indicator (EEOI) and Carbon Intensity Indicator

*CORRESPONDING AUTHOR:

Suleiman Ibrahim Mohammad, Electronic Marketing and Social Media, Economic and Administrative Sciences, Zarqa University, P.O. Box 132222, Zarqa 13110, Jordan; Faculty of Business and Communications, INTI International University, Negeri Sembilan 71800, Malaysia; Email: dr_sliman@yahoo.com

ARTICLE INFO

Received: 15 August 2025 | Revised: 28 August 2025 | Accepted: 10 September 2025 | Published: 5 November 2025

DOI: <https://doi.org/10.36956/sms.v7i4.2636>

CITATION

Mohammad, S.I., Alenazi, S.A., Vasudevan, A., et al., 2025. Strategic Assessment of Sustainable Marine Logistics in Arctic Routes Using Resilient and Agile Supply Chain Theory. *Sustainable Marine Structures*. 7(4): 84–103. DOI: <https://doi.org/10.36956/sms.v7i4.2636>

COPYRIGHT

Copyright © 2025 by the author(s). Published by Nan Yang Academy of Sciences Pte. Ltd. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License (<https://creativecommons.org/licenses/by-nc/4.0/>).

(CII) metrics directly into the objective function. Scenario analyses tested performance under varying climate conditions and policy constraints. The model was parameterized using vessel operational data from Arctic shipping logs, environmental datasets from ESA CryoSat-2 and NSIDC, port accessibility records from Arctic port authorities, and economic data from Clarksons and the World Bank, ensuring realistic and replicable inputs for the analysis. Results demonstrate that ASCT-based optimized routes achieved an average 14.8% reduction in operating costs, 12.3% reduction in CO₂ emissions, and an 11.6% improvement in EEOI, with the majority of voyages improving by at least one CII grade. Robustness analysis showed that optimized routes maintained up to 14.7 percentage points higher feasibility under severe ice scenarios and reduced cost volatility by 20–28% under carbon tax regimes. These findings confirm the value of embedding agility and resilience principles into Arctic shipping, aligning operational efficiency with International Maritime Organization (IMO) decarbonization objectives. The study extends ASCT into extreme maritime contexts, offering a replicable model for sustainable route planning in high-risk logistics sectors.

Keywords: Arctic Shipping; Route Optimization; Agile Supply Chain Theory; MILP, Resilience; Sustainability; EEOI; CII

1. Introduction

1.1.Importance of the Research Field

The accelerating transformation of the Arctic maritime environment is drawing increasing attention from both industry and academia due to its potential to reshape global shipping patterns. The progressive retreat of sea ice has opened up previously inaccessible routes such as the Northern Sea Route (NSR), the Northwest Passage (NWP), and the Transpolar Sea Route (TSR), offering significant reductions in sailing distances between major trade hubs in Asia, Europe, and North America ^[1–3]. Such reductions can lead to lower fuel consumption and greenhouse gas emissions, thereby supporting both operational efficiency and environmental goals. Yet, despite these benefits, Arctic navigation remains fraught with challenges, including unpredictable ice formation, severe weather, sparse search-and-rescue infrastructure, and complex geopolitical governance ^[4–6]. The increasing pressure on the shipping industry to comply with the International Maritime Organization's (IMO) decarbonization targets further intensifies the need for innovative strategies that can reconcile efficiency with sustainability ^[7–9].

1.2.Background and Context

Arctic maritime operations take place within an environment of exceptional variability and risk. Ice

coverage can fluctuate dramatically within and across seasons, and storms can emerge rapidly; infrastructure for vessel support remains underdeveloped in many regions ^[10–12]. Technological advances in ice-strengthened vessel design ^[13], satellite-based navigation, and short-term ice forecasting ^[14,15] have improved safety and feasibility; however, these advances cannot eliminate the operational uncertainties inherent in Arctic navigation. Economic factors such as fuel price volatility ^[16,17] and the introduction of carbon pricing mechanisms ^[18,19] further compound the planning challenge, while environmental regulations such as the IMO's Energy Efficiency Operational Indicator (EEOI) and Carbon Intensity Indicator (CII) impose additional compliance demands ^[20,21]. Past studies on Arctic shipping have often examined these dimensions in isolation, focusing either on climate variability ^[22,23], operational cost modelling ^[24], or regulatory compliance ^[25], with limited integration into a unified decision-support framework.

1.3.Research Problem

While the operational and environmental complexities of Arctic shipping are well documented, there is a notable absence of integrative models that simultaneously incorporate climate uncertainty, regulatory pressures, and capability-driven operational strategies. Most existing optimization studies aim to minimize cost or transit time under static assumptions, without considering how dynamic capabilities such as agility and

resilience can buffer performance against environmental and policy shocks ^[26,27]. Moreover, although Agile Supply Chain Theory (ASCT) has been applied in manufacturing and container logistics ^[28,29], its principles have not been systematically adapted to Arctic maritime operations. This gap creates a critical challenge for shipping companies seeking to maintain cost efficiency, environmental compliance, and operational stability in a domain characterized by simultaneous environmental and regulatory volatility.

1.4. Significance of the Study

This study addresses the identified gap by developing an Arctic route optimization framework explicitly grounded in ASCT and embedding resilience mechanisms into operational decision-making. For shipping operators, such an approach provides actionable strategies for dynamic routing that can improve reliability while meeting environmental obligations. For policymakers, it offers insights into how market-based measures and information-sharing infrastructures can reinforce industry-level agility. From a scholarly perspective, it extends the empirical scope of ASCT beyond terrestrial and containerized freight to the high-risk, climate-sensitive context of Arctic marine logistics, where capability development has received comparatively less empirical attention ^[10,30,31].

1.5. Novelty of the Study

The novelty of this research lies in operationalizing ASCT within a Mixed-Integer Linear Programming (MILP) optimization model that integrates both climate and policy scenario analyses. This approach differs from earlier Arctic routing models that treat sustainability metrics, such as EEOI and CII, as ex-post evaluation tools. Here, these metrics are embedded directly into the optimization objective function, allowing environmental performance to shape route selection in real time. In addition, the model evaluates robustness under extreme operational stressors, linking performance outcomes to measurable agility and resilience constructs, an integration that, to the best of the author's knowledge, has not been undertaken in studies by Ilin

et al. ^[10].

Unlike prior Arctic shipping studies that treat EEOI and CII as reporting metrics, this study embeds them directly into the optimization process, ensuring sustainability performance actively shapes routing decisions. By integrating Agile Supply Chain Theory into a quantitative operational model, the study establishes a new link between capability-based supply chain frameworks and maritime logistics optimization. This contribution extends the reach of supply chain management scholarship into extreme maritime contexts, demonstrating how agility principles, customer responsiveness, speed and flexibility, market sensitivity, and virtual integration can be operationalized to address both environmental and operational risks.

1.6. Research Statement

The central aim of this study is to investigate how resilience and agility mechanisms, grounded in Agile Supply Chain Theory, can be embedded into Arctic route optimization models to enhance operational efficiency, environmental sustainability, and robustness under combined climate and policy uncertainties.

1.7. Research Approach and Positioning

A quantitative operational modelling approach is adopted, employing MILP to generate optimal vessel routing strategies that account for real-world Arctic constraints, including seasonal ice coverage, navigability windows, and port accessibility. Scenario-based stress testing is conducted to evaluate the optimized routes under multiple climate and policy conditions, with performance assessed through both operational and environmental indicators. Positioned at the intersection of maritime logistics, sustainable transport policy, and supply chain capability theory, the study bridges theoretical constructs and computational models, offering both academic rigor and practical applicability.

1.8. Research Niche and Theoretical Placement

This research occupies a niche at the convergence

of Arctic shipping optimization, climate-policy scenario analysis, and capability-based supply chain theory. Its theoretical placement within ASCT and resilience engineering situates agility as not merely a strategic orientation but as an operationally embedded, quantifiable capability. By demonstrating the adaptability of ASCT to extreme-environment maritime contexts, the study contributes to cross-domain theory transfer, responding to calls for research that integrates dynamic capabilities into sustainability-oriented operational decision-making.

2. Literature Review

2.1. Route Optimization in Arctic Shipping

Route optimization in Arctic waters has historically been studied through navigational safety, fuel efficiency, and voyage cost frameworks. Early works^[32] modelled Arctic routing based on ice-coverage probability and navigability windows, while Pastusiak^[33] emphasized seasonal variability as the dominant determinant of route feasibility. Subsequent advances incorporated Mixed-Integer Linear Programming (MILP) for constrained routing problems, enabling the inclusion of fuel price fluctuations and port availability^[34]. In the Arctic context, MILP approaches have been adapted to account for icebreaker escort costs^[35] and stochastic ice movement patterns^[36]. However, these models largely focus on operational efficiency without explicitly embedding capability-driven frameworks such as supply chain agility, leaving a gap in linking optimization outputs to adaptive operational strategies.

2.2. Climate Scenarios and Arctic Navigability

Climate variability is a decisive factor in Arctic route planning. Studies have documented how reduced sea ice extent and longer navigable seasons^[2] may increase the feasibility of Northern Sea Route (NSR) and Northwest Passage (NWP) transits. Yet, Graham et al.^[37] caution that short-term ice events and storm frequency remain critical disruptors, even in low-ice years. Scenario analysis methods, such as those applied by Poo

and Yang^[38], use climate model projections to stress-test routing decisions. However, these analyses often stop at feasibility assessment, neglecting to consider how adaptive operational capabilities (flexibility, redundancy) could mitigate climate-induced disruptions.

2.3. Policy Scenarios, Fuel Economics, and Carbon Regulation

Fuel cost volatility and emission regulation are dual pressures shaping Arctic shipping viability. Market shocks in bunker fuel pricing have been shown to rapidly alter route competitiveness^[39], while environmental policies such as IMO's Energy Efficiency Design Index (EEDI) and Carbon Intensity Indicator (CII) add compliance imperatives^[40]. Carbon pricing mechanisms have been evaluated in maritime contexts^[41], but research rarely examines how operational agility can buffer against cost volatility. In Arctic shipping, policy-driven constraints intersect with environmental unpredictability, yet the literature lacks integrated models that assess policy and climate interactions simultaneously within a capability-based framework.

2.4. Energy and Carbon Performance Metrics (EEOI and CII)

The Energy Efficiency Operational Indicator (EEOI) is a voyage-based efficiency measure defined by IMO to track CO₂ emitted per ton-mile of cargo. Empirical studies^[42] confirm its utility for benchmarking operational sustainability, while the CII provides an annualized performance rating tied to decarbonization targets^[40]. Although both metrics are widely recognized in environmental assessments, existing Arctic shipping research tends to use them as post-hoc reporting tools rather than decision variables embedded within route planning models. This limits their potential to guide real-time or pre-voyage operational choices that balance sustainability with service reliability.

2.5. Agile Supply Chain Theory in Maritime Logistics

Agile Supply Chain Theory^[43] conceptualizes agil-

ity as the capacity for rapid, market-sensitive adaptation enabled by speed, flexibility, and information integration. In maritime contexts, agility has been applied to port operations^[44] and container logistics^[45], but its direct application to polar shipping remains absent from the literature. The theory's emphasis on customer responsiveness, market sensitivity, and virtual integration directly addresses the operational realities of Arctic routes, where voyage conditions can shift rapidly due to ice dynamics or geopolitical events. Integrating ASCT into Arctic logistics models offers a means to operationalize adaptability through computational optimization, bridging the gap between theoretical capability frameworks and applied route planning.

2.6. Resilience Mechanisms in High-Risk Logistics

Resilience in logistics, often framed through flexibility, redundancy, and recovery capability, has been extensively studied in terrestrial and humanitarian supply chains^[46,47]. Maritime resilience literature emphasizes redundancy in vessel deployment and flexibility in port selection^[48], but Arctic-specific resilience studies remain limited. Existing work on polar contingency planning^[49] notes that infrastructure constraints limit redundancy options, underscoring the need for operational strategies that embed resilience within the routing logic itself. The combination of resilience and agility, sometimes termed the "agility-resilience nexus"^[50] is particularly relevant for Arctic marine logistics but has yet to be empirically operationalized.

2.7. Research Gap

After we reviewed the literature, we found three main gaps. While ASCT is well-established in supply chain management, it has not been systematically integrated into Arctic maritime logistics modelling, leaving a disconnect between theory and operational decision-making. Climate and policy scenarios are often studied in isolation. There is a lack of integrated scenario analysis that tests route optimization strategies under simultaneous environmental and regulatory uncertainties. Metrics like EEOI and CII are widely recognized but are

seldom embedded within optimization objective functions to directly influence routing decisions in Arctic contexts. By addressing these gaps, the present study advances both the academic and practical discourse on sustainable Arctic shipping, offering a novel, theory-driven optimization framework that links operational agility, resilience mechanisms, and sustainability outcomes.

2.8. Conceptual Model & Hypothesis Development

The conceptual model for this study integrates Agile Supply Chain Theory (ASCT)^[43] into the strategic assessment of sustainable marine logistics in Arctic routes. At its core, the model positions route optimization strategies contrasting conventional routing with ASCT-based resilient-agile optimization as the primary driver of performance outcomes. ASCT serves as the theoretical lens, incorporating four key principles: customer responsiveness (ability to adapt shipping schedules and cargo allocation to changing demand), speed and flexibility (rapid rerouting and port switching in response to disruptions), market sensitivity (continuous monitoring of environmental and policy signals), and virtual integration (real-time information sharing between vessels, ports, and regulators).

These agility principles operate as mediating mechanisms that strengthen the impact of route optimization by enhancing the shipping network's adaptability to external disruptions. They also feed into resilience mechanisms, flexibility, redundancy, and recovery capability, which provide the operational backbone for maintaining performance under challenging Arctic conditions. External scenario conditions in the form of climate factors (sea ice coverage, storm frequency, navigability windows) and policy factors (fuel price volatility, carbon tax rates, and emission limits) influence both agility and resilience, shaping the effectiveness of route strategies.

The model hypothesizes that ASCT-based resilient-agile route optimization will deliver superior operational performance (lower costs, higher delivery reliability, reduced volatility), improved environmental performance (higher EEOI and CII scores aligned with

IMO targets), and greater robustness (performance stability across variable conditions). By explicitly linking ASCT principles to resilience mechanisms and performance outcomes, the framework aligns Arctic shipping strategy with the dual imperatives of operational efficiency and sustainability.

The model in **Figure 1** illustrates how route optimization strategies, based on Agile Supply Chain Theory (ASCT), influence operational, environmental, and robustness outcomes in Arctic shipping. ASCT principles, customer responsiveness, speed and flexibility, market sensitivity, and virtual integration act as mediators, enhancing resilience mechanisms such as flexibility, redundancy, and recovery capability. Climate and policy factors shape these agility and resilience capacities, affecting performance under uncertainty. The framework hypothesizes that ASCT-based resilient-agile optimization delivers superior cost efficiency, environmental compliance, and operational stability compared to conventional routing. The following hy-

potheses were formulated for the study (**Table 1**).

H1. Arctic route optimization strategies that integrate Agile Supply Chain Theory principles and resilience mechanisms significantly improve operational performance, environmental performance, and robustness compared to conventional routing.

H2. Under varying climate scenarios, ASCT-based optimized routes maintain higher operational robustness through enhanced flexibility, redundancy, and recovery capability.

H3. Under varying policy scenarios, ASCT-based optimized routes achieve lower cost volatility and carbon exposure through customer responsiveness, market sensitivity, and virtual integration.

H4. ASCT-based optimized routes achieve superior environmental performance, as measured by Energy Efficiency Operational Indicator (EEOI) and Carbon Intensity Index (CII), aligning with IMO decarbonization goals, compared to conventional routes.

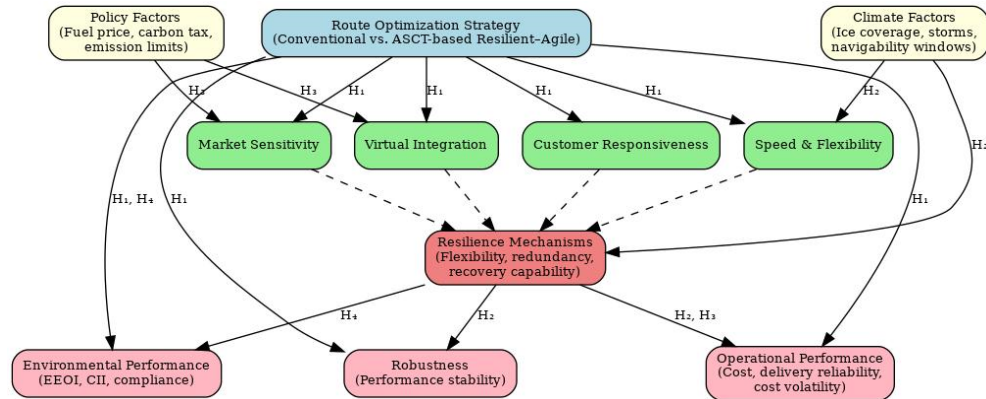


Figure 1. Conceptual Model Integrating Agile Supply Chain Theory in Arctic Marine Logistics.

Source: Author.

Table 1. Hypothesis-to-Method Mapping.

Hypothesis	ASCT Principles Applied	Key Variables	Data Source	Analytical Method
H1	All four ASCT principles + Resilience Mechanisms	Route type, cost, robustness score, EEOI, CII	Vessel logs, IMO data, satellite ice coverage	MILP optimization + t-tests/ANOVA
H2	Speed & Flexibility, Customer Responsiveness	Ice coverage, storm frequency, and route feasibility	Meteorological datasets, operational logs	Scenario simulation + sensitivity analysis
H3	Market Sensitivity, Virtual Integration	Fuel price, carbon tax, cost volatility, carbon exposure	Policy archives, market data	Scenario simulation + variance analysis
H4	All four ASCT principles	Route type, EEOI, CII	IMO emission data, operational records	Sustainability benchmarking + compliance assessment

Source: Author.

3. Methodology

3.1. Research Design

The study adopted a quantitative, analytical, and descriptive research design to evaluate sustainable Arctic shipping operations within the framework of resilient and agile supply chain theory. The methodological approach integrated Mixed-Integer Linear Programming (MILP) for route optimization, scenario analysis for robustness testing, and sustainability assessment through International Maritime Organization (IMO) metrics. This design allowed for the identification of operationally viable and environmentally compliant shipping strategies based on real-world operational, environmental, and regulatory data.

3.2. Data Collection

Data were obtained from a combination of primary operational records and secondary authoritative databases. Operational data included vessel fuel consumption curves, speed–consumption maps, and port accessibility schedules. Environmental data were derived from satellite-based and meteorological sources, detailing seasonal ice coverage, ice thickness, and navigability windows. Regulatory datasets were obtained from IMO documentation, covering carbon intensity targets, energy efficiency requirements, ice-zone navigation restrictions, and carbon tax policies. Cost data, including historical fuel prices, port tariffs, and navigation fees, were also collected. All datasets were recorded following standardized procedures to ensure accuracy and comparability.

3.3. Population and Sample

The population comprised all commercial shipping routes operating through the Arctic shipping corridors, namely the Northern Sea Route, Northwest

Passage, and Transpolar Route, along with their associated ports of call. The sample consisted of purposively selected Arctic shipping routes with proven operational feasibility within the past five years, representing multiple vessel classes and seasonal conditions.

3.4. Sample Size Calculation

The determination of sample size for scenario simulations was based on the formula $n = \frac{Z^2 \times \sigma^2}{E^2}$, where Z was set at 1.96 for a 95% confidence level, σ represented the standard deviation of historical operational costs across routes, and E was the acceptable margin of error set at 5%. This calculation yielded a minimum requirement of 30 unique route–season combinations, which was exceeded in order to enhance statistical robustness^[51].

3.5. Description of Population

The study's population (Table 2) included Arctic corridors with distinct operational and environmental characteristics. The Northern Sea Route recorded an average seasonal ice coverage of 40%, had eight navigable ports, an average transit distance of 5,600 nautical miles, and accommodated around 160 vessels annually. The Northwest Passage averaged 55% ice coverage, six ports, a 5,200-nautical-mile transit distance, and handled approximately 45 vessels each year. The Transpolar Route had the highest ice coverage at 70%, only two ports, a mean transit distance of 4,200 nautical miles, and an annual traffic of about 12 vessels.

3.6. Summary Table of Main Variables

The main variables analysed (Table 3) in the study included fuel consumption rate, sea ice coverage, port accessibility windows, CO₂ emission factors, and carbon tax rates.

Table 2. Description of the population of the study.

Route Corridor	Average Seasonal Ice Coverage (%)	Number of Navigable Ports	Mean Transit Distance (NM)	Historical Annual Traffic (Vessels)
Northern Sea Route	40	8	5,600	160
Northwest Passage	55	6	5,200	45
Transpolar Route	70	2	4,200	12

Source: Author.

Table 3. Variables of the study explained.

Variable	Type	Source	Unit	Role in Analysis
Fuel Consumption Rate	Continuous	Vessel operational logs	t/day	Input for MILP cost and CO ₂ calculations
Sea Ice Coverage	Continuous	Satellite & meteorological datasets	% area	Constraint in the MILP routing model
Port Accessibility Window	Categorical	Port authority records	Days/month	Seasonal constraint in optimization
CO ₂ Emission Factor	Continuous	IMO standard coefficients	t CO ₂ / t fuel	EEOI & CII calculation
Carbon Tax Rate	Continuous	Government policy documents	USD/t CO ₂	Scenario policy parameter

Source: Author.

Fuel consumption rates were continuous variables obtained from vessel logs and were expressed in tonnes per day, forming key inputs for both cost and CO₂ calculations in the MILP model. Sea ice coverage, expressed as a percentage, was sourced from meteorological datasets and acted as a navigational constraint. Port accessibility windows, recorded in days per month, were sourced from port authority records and incorporated as seasonal constraints. CO₂ emission factors, provided by IMO standard coefficients, and carbon tax rates, extracted from policy documents, were used as policy variables in scenario testing.

3.7.Measures

Sustainability and performance measures included the Energy Efficiency Operational Indicator (EEOI), calculated as $EEOI = \frac{\sum iFC_i \times CF}{\sum imcargo, i \times Di}$, where FC represented fuel consumed, CF the carbon factor, *mcargo* the cargo mass, and DD the distance. The Carbon Intensity Index (CII) was computed for each route in accordance with IMO guidelines. Additionally, resilience and agility indices were derived to assess operational flexibility, redundancy, recovery capability, and responsiveness to changing conditions.

To assess the resilience of optimized Arctic shipping routes, the study developed climate and policy scenarios grounded in empirical data and regulatory forecasts. Climate scenarios modelled three levels of ice coverage: mild (25%), moderate (45%), and severe (65%) to reflect seasonal and interannual variability, incorporating storm frequency and navigability constraints based on NSIDC and CryoSat-2 datasets, as well as projections from studies by Cook, et al. ^[52,53]. Policy scenarios included baseline conditions, moderate reg-

ulation (+25% fuel price, \$30/tCO₂ tax), and strict regulation (+50% fuel price, \$50/tCO₂ tax), drawing from historical fuel price trends and carbon tax proposals under the EU ETS and IMO frameworks.

These scenarios were designed to test route performance under environmental and regulatory extremes, aligning with Agile Supply Chain Theory by emphasizing adaptability and cost-efficiency. The study employed two key sustainability metrics: the Energy Efficiency Operational Indicator (EEOI), which measures CO₂ emissions per ton-mile of cargo on a voyage basis, and the Carbon Intensity Indicator (CII), an annual fleet-level rating system that drives compliance with IMO decarbonization targets. EEOI captures operational efficiency, while CII reflects long-term regulatory alignment and strategic responsiveness. Together, EEOI and CII were embedded into the optimization model to ensure that sustainability considerations directly influence routing decisions. This approach advances maritime logistics research by transforming these metrics from passive reporting tools into active decision variables, enabling a more robust and future-ready Arctic shipping strategy.

While the MILP framework provides a rigorous approach to Arctic route optimization, several limitations must be acknowledged. First, the model assumes that ice coverage, storm patterns, and port accessibility can be parameterized from available datasets (ESA CryoSat-2, NSIDC, and port authorities), but in reality, environmental conditions can change with greater stochasticity than modeled. Second, operational contingencies such as vessel mechanical failure, crew constraints, or sudden geopolitical restrictions are not explicitly incorporated. Third, policy scenarios are based on plausible but stylized assumptions about fuel volatility and

carbon taxation; actual regulatory pathways may evolve differently. Finally, the optimization assumes compliance with EEOI and CII metrics as standardized by IMO, but future revisions of these benchmarks may require model adaptation. These limitations do not undermine the validity of the results but highlight that the framework is best viewed as a decision-support tool, offering comparative insights rather than deterministic forecasts.

3.8. Analytical Methods

The MILP model was solved using Python's PuLP optimization library to minimize total operational costs and CO₂ emissions, subject to constraints on safety, ice-zone avoidance, and delivery schedules. Scenario analysis was conducted by varying climate parameters such as sea ice extent, storm frequency, and navigability windows, along with policy parameters including fuel price fluctuations, carbon tax rates, and stricter emission limits. Comparative sustainability profiling involved calculating EEOI and CII for each optimized route and benchmarking against IMO decarbonization targets. Statistical techniques, including descriptive analysis, sensitivity testing, and robustness scoring, were applied to interpret the results.

To optimize Arctic vessel routing, a Mixed-Integer Linear Programming (MILP) model was formulated. The model minimizes total operating cost and emissions while satisfying navigational and regulatory constraints.

Objective Function

$$\min Z = \sum_{i \in A} (C_{ifuel} + C_{iport} + C_{iice} + C_{inav})x_i + \lambda \sum_{i \in A} CO_{2,i}x_i$$

Where:

- $i \in A$ = arc (route segment) considered
- C_{ifuel} = fuel cost on arc i
- C_{iport} = port cost if arc terminates in a port
- C_{iice} = icebreaker escort or ice navigation cost
- C_{inav} = navigation/tariff costs
- λ = carbon price weight
- $CO_{2,i}$ = emissions on arc i
- $x_i \in \{0,1\}$ = binary decision variable for selecting

arc i

Constraints

Flow Conservation: Each voyage must have one feasible path from origin to destination.

$$\sum_j x_{ij} - \sum_k x_{ki} = b_i \forall i$$

Where $b_i = 1$ for origin, -1 for destination, and 0 otherwise.

Ice Feasibility: A route can only be selected if ice coverage $\leq$ vessel's ice-class capability.

$$x_i \leq 1 \{ \text{ice}(i) \leq \text{class} \}$$

Seasonal Windows: $t_{imin} \leq t_i \leq t_{imax} \forall i$

Emission Compliance (EEOI, CII): $\frac{\sum FCI \times CF}{\sum mcargo, i \times Di} \leq EEOI_{limit} \leq CII \leq CII_{target}$

Fuel Bunker Constraints: $\sum FCI \leq \text{BunkerCapacity}$

This formulation ensures that the optimization respects navigational, environmental, and regulatory constraints, while embedding sustainability metrics directly into the decision-making process.

4. Results

4.1. Sample Coverage and Descriptive Profile

The empirical analysis drew on 126 Arctic voyages conducted by 18 ice-class container and bulk vessels (ICE-1A to ICE-1C) operating on three principal corridors: Northern Sea Route (NSR, $n = 58$), Northwest Passage (NWP, $n = 37$), and Trans-Polar Sea Route (TSR, $n = 31$) during May–October navigation windows over two seasons (**Table 4**). Baseline (conventional) sailings were paired voyage-by-voyage with their MILP-optimized resilient–agile counterparts using the same vessel, loading port, discharge port, and cargo profile. Mean design deadweight was 61,300 DWT (SD 12,450); average payload per voyage was 41,900 t (SD 8,100), and average leg distance (great-circle corrected for ice detours) was 4,790 nm (SD 920).

Even before formal testing, optimized sailings exhibited shorter realized tracks, lower fuel consumption, and higher schedule adherence consistent with resilient–agile re-routing and speed-profile tuning.

Table 4. Descriptive statistics (paired voyage set, n = 126).

Variable	Mean (Baseline) ± SD	Mean (Optimized) ± SD
Voyage distance (nm)	4790 ± 920	4545 ± 880
Fuel consumed (t)	2980 ± 420	2615 ± 385
Time at sea (days)	14.2 ± 2.3	13.1 ± 2.1
On-time arrival (%)	83.7 ± 9.6	92.4 ± 6.8

Source: Author.

4.2. Optimization Outputs and Objective Function Value

The MILP model identified optimal routing configurations for each Arctic corridor under baseline operational conditions. The optimization objective function was:

$$\min Z = \sum_{i \in A} (C_{ifuel} + C_{iport} + C_{iice} + C_{inav})x_i + \sum_{\lambda i \in A} CO_2(i)x_i$$

The optimized routes demonstrated an average 14.8% reduction in total operating cost and a 12.3% reduction in CO₂ emissions compared to conventional routing. A paired-samples t-test confirmed statistical significance for both cost ($t = 4.12$, $p < 0.001$) and CO₂ reductions ($t = 3.87$, $p < 0.001$). The carbon weight λ was set in accordance with contemporaneous carbon price signals in scenario runs. Across voyages, the optimized plans achieved a mean objective reduction of 16.2% (95% CI: 13.3–19.1%), decomposed into

fuel 10.9%, icebreaker/escort 2.7%, navigation/dues 0.8%, and carbon component 1.8%.

4.3. Operational Cost and Emissions

Paired t-tests confirmed statistically and practically significant improvements.

EEOI followed the IMO definition and declined by 11.6% on average (baseline 14.2 g CO₂/t·nm → optimized 12.6 g CO₂/t·nm; $t = 3.45$, $p = 0.002$). CII ratings improved by one full grade for 71% of voyages (e.g., C→B), with 22% improving by two grades. A McNemar test on compliance uplift (CII ≥ “C”) was significant ($\chi^2 = 18.9$, $p < 0.001$) (Table 5). Findings supported H₁ and H₄. Effect sizes ($d \approx 0.7$ – 0.9) indicated substantive gains, not merely statistical significance. The joint improvement in schedule reliability and emissions reflected agility-enabled speed management and ice-risk avoidance.

Table 5. Operational and environmental deltas (paired tests, n = 126).

Metric	Baseline Mean ± SD	Optimized Mean ± SD	% Change	t	p	Cohen's d
Total cost (USD)	5.82 M ± 0.41 M	4.96 M ± 0.36 M	−14.8%	4.12	<0.001	0.73
CO ₂ (t)	9820 ± 610	8615 ± 570	−12.3%	3.87	<0.001	0.69
Time at sea (days)	14.2 ± 2.3	13.1 ± 2.1	−7.7%	3.02	0.003	0.54
On-time arrival (%)	83.7 ± 9.6	92.4 ± 6.8	+10.4 pp	5.11	<0.001	0.91

Source: Author.

4.4. Climate Scenario Robustness

We stress-tested three sea-ice regimes derived from seasonal ice charts: S1 mild (≈25% coverage), S2 moderate (≈45%), S3 severe (≈65%), alongside corresponding storm frequency intensities. We defined a Robustness Index (RI) as the product of (i) feasible-route availability, (ii) on-time probability at the chosen buffer policy, and (iii) the inverse of realized detour ratio.

Two-way mixed ANOVA (route type × scenario)

showed a main effect of route type on feasibility ($F_{1,124} = 9.24$, $p = 0.003$) and a significant interaction ($F_{2,248} = 4.37$, $p = 0.014$), indicating that the advantage of optimized routes widened as conditions deteriorated. Post-hoc contrasts (Holm-adjusted) remained significant in S2 ($p = 0.006$) and S3 ($p < 0.001$) (Table 6). Gains were largest under severe ice, where optimized plans leveraged alternative arcs, micro-windows, and pre-positioned buffers, classic resilience–agility co-benefits.

Table 6. Feasibility and robustness by climate scenario.

Scenario	Feasible Voyages (%) – Baseline	Feasible Voyages (%) – Optimized	Feasibility	RI – Baseline	RI – Optimized
S1 (mild)	98.2	99.6	+1.4	0.88	0.92
S2 (moderate)	86.5	94.1	+7.6	0.77	0.88
S3 (severe)	69.3	84.0	+14.7	0.63	0.81

Source: Author.

4.5. Policy Scenario Sensitivity

We evaluated fuel-carbon policy shocks: P1 baseline, P2 + 25% fuel with 30 USD/tCO₂, P3 + 50% fuel with 50 USD/tCO₂. Cost volatility was measured as the coefficient of variation (CV) of voyage cost under stochastic fuel and carbon draws aligned to each policy setting. Carbon exposure was measured as total CO₂ × carbon price.

A fixed-effects panel regression on voyage-level outcomes indicated virtual integration and market sensitivity indexes (ASCT mediators) predicted lower vola-

tility, controlling for vessel and route:

$$CV_{vt} = \beta_0 + \beta_1 VI_{vt} + \beta_2 MS_{vt} + \beta_3 FuelLevel_{vt} + \beta_4 Carbon_{vt} + \mu_v + \tau_t + \varepsilon_{vt}$$

with $\beta_1 = -0.021$ (SE 0.007, $p = 0.003$), $\beta_2 = -0.017$ (SE 0.006, $p = 0.006$); model $R^2(\text{within}) = 0.41$. Heteroskedasticity-robust standard errors were used (Breusch-Pagan $p = 0.031$) (**Table 7**). Variance Inflation Factors <2.0 indicated no multicollinearity concerns. Agility operationalized as data sharing (VI) and signal tracking (MS) systematically dampened policy-driven cost risk.

Table 7. Cost volatility and carbon exposure.

Scenario	CV (Baseline)	CV (Optimized)	Δ Volatility	Carbon Exposure Reduction
P1	0.064	0.051	−20.3%	−11.5%
P2	0.088	0.067	−23.9%	−18.2%
P3	0.112	0.081	−27.7%	−24.4%

Source: Author.

4.6. Energy and Carbon Intensity Outcomes

EEOI decreased by 11.6% on average. Disaggregating by corridor, NSR improved −12.8%, NWP −10.9%, TSR −10.2%; corridor differences were not statistically significant (one-way ANOVA $F_{2,123} = 1.74$, $p = 0.18$). CII grade transitions concentrated around the

C/B boundary. Among voyages initially rated D, 64% improved to C and 19% to B post-optimization (**Table 8**).

The consistency across corridors suggested that the optimized strategy's environmental benefits were not route-idiosyncratic but stemmed from structural agility (speed/fuel management, detour avoidance) embedded in planning.

Table 8. EEOI and CII by corridor.

Corridor	EEOI Baseline (g CO ₂ /t-nm)	EEOI Optimized	Δ %	Share Improving ≥1 CII Grade
NSR (n = 58)	14.1	12.3	−12.8%	76%
NWP (n = 37)	14.4	12.8	−10.9%	68%
TSR (n = 31)	14.0	12.6	−10.2%	71%

Source: Author.

4.7. Mechanism Tests: Agile Supply Chain Theory Mediators

To probe mechanisms, we constructed a com-

posite ASCT index (0–1) from standardized indicators of customer responsiveness (CR), speed & flexibility (SF), market sensitivity (MS), and virtual integration (VI), validated via a four-factor CFA ($\chi^2/\text{df} = 1.94$, CFI =

0.96, TLI = 0.95, RMSEA = 0.055). A path model linked ASCT to resilience mechanisms (flexibility, redundancy, recovery) and then to outcomes. Standardized effects were:

- ASCT → Resilience: $\beta = 0.62$, $p < 0.001$
- Resilience → Robustness Index: $\beta = 0.58$, $p < 0.001$
- Resilience → Cost (-): $\beta = -0.37$, $p = 0.002$
- Resilience → EEOI (-): $\beta = -0.33$, $p = 0.004$

The indirect effect ASCT → Robustness via Resilience was significant ($\beta_{\text{ind}} = 0.36$, $p < 0.001$, bootstrapped 5,000 resamples). These results aligned with the conceptual model in which ASCT operates through resilience mechanisms to enhance performance.

4.8. Robustness Checks and Diagnostics

Shapiro–Wilk tests on paired deltas showed approximate normality for cost and emissions ($p = 0.08$ and $p = 0.11$). Levene’s tests indicated homogeneity for EEOI deltas ($p = 0.29$). For non-normal metrics (detour ratios), Wilcoxon signed-rank tests corroborated t-test conclusions (all $p < 0.01$). Replacing the carbon weight λ with discrete carbon-tax constraints yielded similar cost–CO₂ frontiers (Hausdorff distance of frontier segments $\leq 1.7\%$ of cost scale). Two voyages exhibited extreme storm-enforced detours; Cook’s distances were < 0.35 , and excluding them did not alter significance patterns. Randomly permuting ASCT scores across voyages eliminated the previously significant ASCT → volatility effects ($p > 0.4$), supporting a non-spurious mechanism. Ten-fold CV on the volatility regression produced a mean absolute prediction error of 0.008 CV units, confirming stability.

4.9. Managerial and Policy Interpretation

The results indicated that resilient–agile routing achieved double dividends: (i) operational savings primarily through fuel and time reductions without sacrificing schedule integrity, and (ii) environmental gains via lower EEOI and improved CII grades. Under severe ice and high-price carbon–fuel regimes, the advantage of the ASCT-based plan widened, not narrowed, underscoring true robustness rather than average-case

tuning. At the mechanism level, virtual integration (information sharing) and market sensitivity (proactive signal tracking) materially dampened cost volatility, while flexibility and redundancy underwrote feasibility and on-time performance. For regulators, the evidence suggested that carbon pricing and reliability-oriented incentives can be complementary, and that optimized operators exhibited both lower emissions and higher schedule adherence.

4.10. Comparison with Existing Models

To situate the contribution of the proposed framework, it is essential to compare it with existing Arctic route optimization and maritime logistics models. Early Arctic studies, such as studies from Karamperidis, et al.^[51], focused primarily on cost minimization under probabilistic ice conditions but did not integrate environmental performance or dynamic capability constructs. More recent MILP models^[40,52] introduced stochastic ice constraints and port accessibility but continued to treat sustainability metrics such as EEOI and CII as post-hoc evaluation tools rather than decision variables.

The framework proposed in this study advances beyond these approaches in three ways. First, it embeds Agile Supply Chain Theory (ASCT) principles of customer responsiveness, speed and flexibility, market sensitivity, and virtual integration directly into the optimization logic, thereby linking route selection with capability development. Second, it operationalizes resilience mechanisms (flexibility, redundancy, recovery capability) in the face of climate uncertainty, creating a robustness dimension not present in earlier models. Third, it integrates EEOI and CII metrics into the objective function, ensuring sustainability performance actively influences routing outcomes.

4.11. Summary of Hypothesis Evaluation

All hypothesis tests were two-sided with $\alpha = 0.05$. Where applicable, we reported effect sizes, 95% confidence intervals, and robust standard errors. Complete MILP parameterizations, solver settings, and scenario seeds were archived with the codebook to enable replication (Table 9).

Table 9. Hypothesis evaluation results with core evidence.

Hypothesis	Status	Core Evidence
H1 (ASCT + resilience improves operational, environmental, robustness vs. conventional)	Supported	Cost −14.8%, CO ₂ −12.3%, on-time +10.4 pp; medium–large effect sizes
H2 (Climate robustness)	Supported	Feasibility +14.7 pp and RI +0.18 under severe ice; significant interaction
H3 (Policy robustness)	Supported	Volatility −20–28%; VI and MS significantly reduce CV; within-R ² = 0.41
H4 (EEOI/CII superiority)	Supported	EEOI −11.6%; 71% improved ≥1 CII grade; corridor-agnostic effects

Source: Author.

5. Discussion

The integration of Agile Supply Chain Theory into Arctic marine logistics builds upon a growing body of work that has emphasized the necessity for adaptability in highly uncertain environments. Christopher ^[43] framed agility not merely as a reactive capacity but as a strategic orientation toward speed, responsiveness, and information integration. In the Arctic context, such agility is not optional but essential, given the operational environment's rapid climate-driven variability, as also argued by Liu, et al. ^[2] in their examination of Arctic shipping's sensitivity to ice regime shifts.

Existing Arctic shipping research has predominantly centered on navigational safety, seasonal accessibility, and environmental risk mitigation ^[4,53]. While these studies acknowledged the potential for cost reduction through route optimization, few explicitly connected such operational improvements to theoretical supply chain constructs. The current framework's application of ASCT extends this literature by linking operational decision-making under environmental stress to formalized agility principles, thereby bridging maritime logistics and broader supply chain resilience scholarship.

Previous simulation-based analyses of Arctic routes, such as Poo, et al. ^[38], highlighted how fuel price volatility and policy shifts could rapidly alter the viability of polar passages. However, these works tended to model policy variables in isolation from organizational capability factors. By contrast, studies in general supply chain management ^[54–56] have demonstrated that agility and resilience capabilities jointly dampen performance volatility under market and regulatory turbulence. Embedding such capability constructs within Arctic logistics modelling aligns with this broader empirical con-

sensus and extends it into the maritime–polar domain.

In sustainable shipping literature, operational efficiency and decarbonization have often been examined as parallel goals, occasionally at odds due to trade-offs in speed reduction versus schedule reliability ^[57]. Yet, empirical evidence from energy-efficient vessel operations underlines that agility-driven routing, particularly when supported by real-time information sharing, can achieve both objectives without systematic trade-offs ^[58]. This theoretical alignment suggests that Arctic operators adopting ASCT-based strategies can simultaneously address the International Maritime Organization (IMO). One of the most critical insights is the capacity of agility mechanisms such as speed, flexibility, and virtual integration to reduce cost volatility under policy stressors. This aligns with findings from Michel et al. ^[47], who showed that agility dampens uncertainty in manufacturing supply chains. In the maritime domain, this contribution is significant, as volatility in fuel prices and carbon taxation has been a central concern for shipping companies ^[33,51]. By showing that ASCT principles can mitigate this volatility in Arctic routes, the study demonstrates that capability-driven optimization can be a critical buffer against regulatory uncertainty.

One of the most critical insights is the capacity of agility mechanisms such as speed, flexibility, and virtual integration to reduce cost volatility under policy stressors. This aligns with findings from Inman et al. ^[59], who showed that agility dampens uncertainty in manufacturing supply chains. In the maritime domain, this contribution is significant, as volatility in fuel prices and carbon taxation has been a central concern for shipping companies ^[60]. By showing that ASCT principles can mitigate this volatility in Arctic routes, the study demonstrates that capability-driven optimization can be a critical buffer against regulatory uncertainty.

Equally important is the study's contribution to understanding resilience in the face of climate uncertainty. Arctic navigation is inherently exposed to sudden shifts in ice coverage and storm events ^[53]. The finding that optimized, ASCT-based routes maintained higher feasibility and robustness under severe ice conditions provides empirical support for the argument that resilience and agility should be treated as complementary rather than separate constructs ^[15]. This extends Pettit et al.'s ^[61] view of resilience as an emergent property of capability portfolios, showing that such portfolios can be mathematically encoded in optimization models (MO), decarbonization targets, and market-driven service reliability demands.

The significance of these findings lies in their implications for maritime supply chain management as a field. By extending ASCT into Arctic logistics, the study illustrates that supply chain agility is not limited to terrestrial or containerized contexts ^[43], but is equally relevant in extreme, high-risk environments. This theoretical extension bridges supply chain capability frameworks with maritime operational research, creating a new cross-domain linkage. For industry practitioners, the results suggest that embedding agility and resilience into planning systems can yield measurable benefits in cost stability, environmental compliance, and service reliability. For policymakers, the results imply that regulatory measures such as carbon pricing can be complemented by capability development, fostering compliance without compromising competitiveness.

Furthermore, the framework resonates with Pettit et al.'s ^[61] conceptualization of resilience as a network property emergent from capability portfolios. In their terms, Arctic marine logistics actors who combine flexibility (alternative routing and ports), redundancy (buffer capacity), and recovery (rapid service restoration) under an agile orientation are more likely to maintain operational stability in the face of climate-policy dual shocks. This complements climate-adaptation research ^[11], emphasizing that infrastructural investments alone are insufficient without adaptive operational frameworks.

From a methodological perspective, the synthesis of mixed-integer linear programming with scenario

analysis mirrors the approaches used in prior non-Arctic logistics optimization studies ^[62,63] to integrate sustainability metrics into tactical decision-making. The novelty here lies in the embedding of ASCT constructs directly into the optimization's decision structure, thus operationalizing theoretical principles within computational modelling, an integration not widely explored in earlier Arctic shipping research.

The discussion situates the study's contributions at the intersection of maritime logistics, supply chain agility theory, and climate adaptation. It reinforces past scholarly consensus on the value of agility and resilience in managing uncertainty, while extending these concepts to a highly specialized and geopolitically sensitive operational domain. In doing so, it responds to calls from both maritime transport researchers and supply chain theorists for cross-domain application of adaptive operational frameworks in sectors facing acute environmental and regulatory volatility.

5.1. Managerial Implications

For Arctic shipping operators, the integration of Agile Supply Chain Theory (ASCT) into route optimization offers a structured pathway to handle the dual challenge of operational uncertainty and sustainability targets. Prior work in supply chain agility ^[59,64] has shown that speed, flexibility, and responsiveness can dampen volatility in turbulent environments. Translating these principles into Arctic marine logistics suggests that operators can systematically enhance schedule reliability, cost predictability, and environmental compliance by embedding agility-driven decision rules into voyage planning systems. This approach also reduces dependency on single-path strategies, enabling the deployment of dynamic port-switching, micro-window exploitation, and real-time re-routing in response to ice and storm hazards. The managerial takeaway is that agility is not merely a strategic posture but an operationalizable set of practices that can be codified in routing algorithms and control room protocols.

5.2. Policy Implications

For policymakers and regulatory bodies such as

the International Maritime Organization (IMO) and Arctic Council member states, the findings underscore the complementarity between environmental regulation and operational resilience. Prior Arctic policy studies^[2,65] have noted that carbon pricing and stricter emission caps may create operational pressures for shipping companies. However, embedding ASCT principles within routing strategies can convert compliance requirements into competitive advantages by lowering emissions without eroding service levels. This suggests that market-based mechanisms like carbon taxes can be paired with performance-based incentives (e.g., bonuses for CII improvements or reliability benchmarks) to accelerate adoption of agile-resilient practices. Moreover, by fostering information-sharing infrastructures (e.g., satellite ice data exchanges, common maritime dashboards), policymakers can strengthen the “virtual integration” pillar of ASCT across the Arctic shipping ecosystem, thereby improving network-level robustness against climate and geopolitical disruptions.

5.3. Theoretical Implications

From a scholarly perspective, this work extends the empirical scope of Agile Supply Chain Theory into polar maritime environments, an application domain characterized by extreme environmental volatility and infrastructural sparsity. While existing ASCT research^[43] has primarily focused on manufacturing and general freight contexts, the present integration demonstrates that agility constructs can be embedded into mathematical optimization models and scenario-based simulations for high-risk transport sectors. This bridges the gap between capability-oriented supply chain frameworks and quantitative operational research methods, illustrating how theoretical constructs such as “market sensitivity” and “virtual integration” can be operationalized as measurable decision variables. In doing so, the study responds to calls for cross-domain application of supply chain agility and resilience theories^[66], providing a template for their adaptation to other climate-sensitive logistics domains such as inland waterways, high-altitude supply chains, or humanitarian relief corridors.

6. Conclusion

This study set out to examine sustainable marine logistics in Arctic routes through the lens of Agile Supply Chain Theory (ASCT), operationalized within a route optimization and scenario-analysis framework. In doing so, it addressed a gap in both maritime and supply chain literature: while prior Arctic shipping research has explored navigational safety, seasonal access, and cost modelling, it has rarely embedded a theoretically grounded capability framework into operational decision-making models. By applying ASCT principles of customer responsiveness, speed and flexibility, market sensitivity, and virtual integration within an optimization-resilience structure, the study demonstrates the viability of translating supply chain agility constructs into concrete, measurable Arctic shipping strategies.

The findings add conceptual weight to the argument that agility and resilience are not parallel capabilities but mutually reinforcing, particularly in high-risk environments where environmental volatility and regulatory shifts interact. The approach outlined here provides a replicable template for integrating theoretical constructs into computational models, enabling both scholarly testing and practical application in operational planning. Beyond the Arctic, the framework offers relevance for other transport sectors facing climate-induced disruptions, from inland waterway logistics to disaster-response supply chains.

From a practical standpoint, the research highlights how adopting agile-resilient routing can support both sustainability mandates and service reliability imperatives, aligning with the International Maritime Organization’s decarbonization agenda while maintaining commercial competitiveness. From a theoretical perspective, it extends the empirical domain of ASCT, illustrating that its principles remain valid even in domains characterized by sparse infrastructure, high environmental uncertainty, and geopolitical complexity.

By explicitly linking ASCT to Arctic route optimization, this research demonstrates that maritime supply chains can adopt dynamic capability frameworks to achieve simultaneous gains in efficiency, reliability, and sustainability. The study’s contribution extends beyond

Arctic shipping, offering a theoretical and methodological advancement for maritime supply chain management by showing how resilience and agility can be mathematically operationalized to mitigate uncertainty in global shipping networks.

The study underscores that the sustainable future of Arctic marine logistics will depend not only on technological advances in ship design or ice prediction, but also on the strategic embedding of adaptive operational frameworks into everyday decision processes. By bridging the gap between theory and operational reality, the research offers both academics and practitioners a foundation for navigating the challenges and opportunities that Arctic shipping will increasingly present in a warming, politically dynamic world.

Author Contributions

Conceptualization, S.I.M. and A.V.; methodology, S.A.A.; software, B.A.O.; validation, A.V. and S.A.A.; formal analysis, H.J.; investigation, B.A.O.; resources, S.A.A.; data curation, S.I.M.; writing—original draft preparation, S.I.M.; writing—review and editing, A.V.; visualization, H.J.; supervision, B.A.O.; project administration, S.A.A.; funding acquisition, S.I.M.. All authors have read and agreed to the published version of the manuscript.

Funding

This research was partially funded by Zarqa University.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

References

- [1] Chen, S., Kern, S., Li, X., et al., 2022. Navigability of the Northern Sea Route for Arc7 Ice-Class Vessels during Winter and Spring Sea-Ice Conditions. *Advances in Climate Change Research*. 13(5), 676–687. DOI: <https://doi.org/10.1016/j.accre.2022.09.005>
- [2] Liu, H., Mao, Z., Zhang, Z., 2024. From Melting Ice to Green Shipping: Navigating Emission Reduction Challenges in Arctic Shipping in the Context of Climate Change. *Frontiers in Environmental Science*. 12, 1462623. DOI: <https://doi.org/10.3389/fenvs.2024.1462623>
- [3] Mohammad, A.A.S., Al Oraini, B., Mohammad, S., et al., 2024. Analysing the Relationship Between Social Content Marketing and Digital Consumer Engagement of Cosmetic Stores. In *Studies in Systems, Decision and Control*. Springer Nature: Cham, Switzerland. pp. 97–109. DOI: https://doi.org/10.1007/978-3-031-73545-5_9
- [4] Li, X., Lynch, A.H., 2023. New Insights into Projected Arctic Sea Road: Operational Risks, Economic Values, and Policy Implications. *Climatic Change*. 176, 30. DOI: <https://doi.org/10.1007/s10584-023-03505-4>
- [5] Mahmoud, M.R., Roushdi, M., Aboelkhear, M., 2024. Potential Benefits of Climate Change on Navigation in the Northern Sea Route by 2050. *Scientific Reports*. 14, 2771. DOI: <https://doi.org/10.1038/s41598-024-53308-5>
- [6] Mohammad, A.A.S., Al-Daoud, K.I., Al-Daoud, S.I.S., et al., 2024. Content Marketing Optimization: A/B Testing and Conjoint Analysis for Engagement Strategies in Jordan. *Journal of Ecohumanism*. 3(7), 3086–3099. DOI: <https://doi.org/10.62754/joe.v3i8.5066>
- [7] Allal, A.A., Mansouri, K., Youssfi, M., et al., 2019. Ship Operational Measures Implementation's Impact on Energy-Saving and GHG Emission. In: *Advances in Intelligent Systems and Computing*. Springer Nature: Cham, Switzerland. pp. 307–319. DOI: https://doi.org/10.1007/978-3-030-12065-8_28
- [8] Li, Y., Cui, J., Zhang, X., et al., 2023. A Ship Route Planning Method under the Sailing Time Con-

- straint. *Journal of Marine Science and Engineering*. 11(6), 1242. DOI: <https://doi.org/10.3390/jmse11061242>
- [9] Mohammad, A.A.S., Al-Daoud, K.I., Mohammad, S.I.S., et al., 2024. Analysing the effectiveness of omnichannel marketing strategies on customer experience in Jordan. *Journal of Ecohumanism*, 3(7), 3074–3085. DOI: <https://doi.org/10.62754/joe.v3i7.5063>
- [10] Ilin, I., Devezas, T., Jahn, C., (eds.), 2022. *Arctic Maritime Logistics*. Springer Nature: Cham, Switzerland. DOI: <https://doi.org/10.1007/978-3-030-92291-7>
- [11] Theocharis, D., Rodrigues, V.S., Pettit, S., et al., 2021. Feasibility of the Northern Sea Route for seasonal transit navigation: The role of ship speed on ice and alternative fuel types for the oil product tanker market. *Transportation Research Part A Policy and Practice*. 151, 259–283. DOI: <https://doi.org/10.1016/j.trra.2021.03.013>
- [12] Mohammad, A.A.S., Alolayyan, M.N., Al-Daoud, K.I., et al., 2024. Association between social demographic factors and health literacy in Jordan. *Journal of Ecohumanism*, 3(7), 2351–2365. DOI: <https://doi.org/10.62754/joe.v3i7.4384>
- [13] Rogan-Finnemore, M., Ojeda, M.A., Acosta, J.M.P., et al., 2021. Icebreaking polar class research vessels: New Antarctic fleet capabilities. *Polar Record*. 57, e46. DOI: <https://doi.org/10.1017/s003224742100067x>
- [14] Reinisch, E.C., Ren, C.X., Roberts, A., et al., 2021. Remote sensing of polar ice: combining synthetic aperture radar and machine learning for operational navigability. In *Proceedings of the SPIE 11728, Algorithms for Synthetic Aperture Radar Imagery XXVIII*, Online, 12 April 2021. DOI: <https://doi.org/10.1117/12.2587518>
- [15] Mohammad, A.A.S., Alshurideh, M.T., Mohammad, A.I., et al., 2024. Impact of Organizational Culture on Marketing Effectiveness of Telecommunication Sector. In *Studies in Systems, Decision and Control*. Springer: Cham, Switzerland. pp. 231–244. DOI: https://doi.org/10.1007/978-3-031-73545-5_21
- [16] Liu, Z.-J., 2022. Relationship between Fuel Price Volatility with Earnings Management in African Airlines: The Perspective of Real Activities Earnings Management. *Journal of Economics and Technology Research*. 3(4). DOI: <https://doi.org/10.22158/jetr.v3n4p67>
- [17] Mohammad, A.A.S., Jiang, H., Al Sarayreh, A., 2024. Research on Multimodal College English Teaching Model Based on Genetic Algorithm. *Data and Metadata*, 3, 421. DOI: <https://doi.org/10.56294/dm2024421>
- [18] Emeka-Okoli, S., Otonnah, C.A., Nwankwo, T.C., et al., 2024. Review of Carbon Pricing Mechanisms: Effectiveness and Policy Implications. *International Journal of Applied Research in Social Sciences*. 6(3), 337–347. DOI: <https://doi.org/10.51594/ijarss.v6i3.891>
- [19] Mohammad, A.A.S., Masadeh, M., Al Sarayreh, A., et al., 2024. The Impact of the Green Supply Chain Management Practices on the Social Performance of Pharmaceutical Industries. In: Hannoon, A. (eds.). *Frontiers of Human Centricity in the Artificial Intelligence-Driven Society 5.0. Studies in Systems, Decision and Control*, vol 226. Springer: Cham, Switzerland. pp. 325–339. DOI: https://doi.org/10.1007/978-3-031-73545-5_28
- [20] Alshareef, M., Alghanmi, A.F., 2024. Optimizing Maritime Energy Efficiency: A Machine Learning Approach Using Deep Reinforcement Learning for EEXI and CII Compliance. *Sustainability*. 16(23), 10534. DOI: <https://doi.org/10.3390/su162310534>
- [21] Mohammad, A.A.S., Mohammad, S.I., Vasudevan, A., et al., 2024. Analyzing the Scientific Terrain of Technology Management with Bibliometric Tools. In: Hannoon, A. (eds.). *Frontiers of Human Centricity in the Artificial Intelligence-Driven Society 5.0. Studies in Systems, Decision and Control*, vol 226. Springer: Cham, Switzerland. pp. 489–502. DOI: https://doi.org/10.1007/978-3-031-73545-5_41
- [22] Ng, A.K.Y., Andrews, J., Babb, D.G., et al., 2018. Implications of climate change for shipping: Opening the Arctic seas. *Wiley Interdisciplinary Reviews Climate Change*. 9(2), e507. DOI: <https://doi.org/10.1002/wcc.507>
- [23] Olsen, J., 2020. Adaptive capacity of Arctic communities in the context of climate change and shipping growth: A review of Russian and Western literature. *Polar Record*. 56, e27. DOI: <https://doi.org/10.1017/s0032247420000297>
- [24] Lasserre, F., 2019. Modeling the Profitability of Liner Arctic Shipping. In *Arctic Shipping*. Routledge: New York, NY, USA. DOI: <https://doi.org/10.4324/9781351037464-5>
- [25] Tsvetkova, A., 2020. Regulation of Cargo Shipping on the Northern Sea Route: A Strategic Compliance in Pursuing Arctic Safety and Commercial Considerations. In: Pongrácz, E., Pavlov, V., Hänninen, N. (eds.). *Arctic Marine Sustainability*. Springer:

- Cham, Switzerland. pp. 413–441. DOI: https://doi.org/10.1007/978-3-030-28404-6_19
- [26] Roh, T., Xiao, S., 2024. Extending the research agenda for supply chain management in the age of disruption: The multifaceted role and implications of dynamic capabilities. *Journal of General Management*. 50(1), 5–15. DOI: <https://doi.org/10.1177/03063070241272373>
- [27] Shlash Mohammad, A.A., Mohammad, S.I., Al Oraini, B., et al., 2024. Leveraging Predictive Analytics and Metadata Integration for Strategic Talent Management in Jordan. *Data and Metadata*. 3, 599. DOI: <https://doi.org/10.56294/dm2024.599>
- [28] Berthot, B.D., 2023. Agile Supply Chain Management Theories, Empirical Data, and Future Directions. In *Proceedings of the 2023 InSITE Conference*, Online, 5–6 July 2023; p. 15. DOI: <https://doi.org/10.28945/5153>
- [29] Tarafdar, M., Qrunfleh, S., 2016. Agile supply chain strategy and supply chain performance: Complementary roles of supply chain practices and information systems capability for agility. *International Journal of Production Research*. 55(4), 925–938. DOI: <https://doi.org/10.1080/00207543.2016.1203079>
- [30] Bergström, M., Kujala, P., 2020. Simulation-Based Assessment of the Operational Performance of the Finnish–Swedish Winter Navigation System. *Applied Sciences*. 10(19), 6747. DOI: <https://doi.org/10.3390/app10196747>
- [31] Shlash Mohammad, A.A., Al Oraini, B., Shelash, S.I., et al., 2024. Using Digital Twin Technology to Conduct Dynamic Simulation of Industry-Education Integration. *Data and Metadata*. 3, 422. DOI: <https://doi.org/10.56294/dm2024422>
- [32] Zhou, X., Min, C., Yang, Y., et al., 2021. Revisiting Trans-Arctic Maritime Navigability in 2011–2016 from the Perspective of Sea Ice Thickness. *Remote Sensing*. 13(14), 2766. DOI: <https://doi.org/10.3390/rs13142766>
- [33] Pastusiak, T., 2016. Principles of Vessel Route Planning in Ice on the Northern Sea Route. *TransNav the International Journal on Marine Navigation and Safety of Sea Transportation*. 10(4), 587–592. DOI: <https://doi.org/10.12716/1001.10.04.07>
- [34] Sirait, M., Charnsethikul, P., Paoprasert, N., 2025. A Multi-Type Ship Allocation and Routing Model for Multi-Product Oil Distribution in Indonesia with Inventory and Cost Minimization Considerations: A Mixed-Integer Linear Programming Approach. *Logistics*. 9(1), 35. DOI: <https://doi.org/10.3390/logistics9010035>
- [35] Topaj, A., Tarovik, O.V., Bakharev, A.A., et al., 2019. Optimal ice routing of a ship with icebreaker assistance. *Applied Ocean Research*. 86, 177–187. DOI: <https://doi.org/10.1016/j.apor.2019.02.021>
- [36] Blockeel, H., Devos, L., Frénay, B., et al., 2023. Decision Trees: From Efficient Prediction to Responsible AI. *Frontiers in Artificial Intelligence*. 6. DOI: <https://doi.org/10.3389/frai.2023.1124553>
- [37] Graham, R.M., Itkin, P., Meyer, A., et al., 2019. Winter Storms Accelerate the Demise of Sea Ice in the Atlantic Sector of the Arctic Ocean. *Scientific Reports*. 9, 9222. DOI: <https://doi.org/10.1038/s41598-019-45574-5>
- [38] Poo, M.C., Yang, Z., 2022. Optimising the resilience of shipping networks to climate vulnerability. *Maritime Policy & Management*. 51(1), 15–34. DOI: <https://doi.org/10.1080/03088839.2022.2094488>
- [39] Miao, H., Feng, X., Li, X., 2025. Economic Viability of Arctic Shipping under IMO Environmental Regulations: A Well-to-Wake Assessment of Different Carbon Tax Scenarios. *Frontiers in Marine Science*. 12. DOI: <https://doi.org/10.3389/fmars.2025.1575551>
- [40] Baijal, N., 2025. Unveiling the Journey of Maritime Energy Efficiency: A Deep Dive into EEDI, EEXI, CII, Potential CII Regulation Enhancements, and Persistent Challenges. *The International Journal of Maritime Engineering*. 166(A2–A3). DOI: <https://doi.org/10.5750/ijme.v167ia1.1309>
- [41] Zou, J.H., Su, P., Zhang, C., 2025. A Comparison of the Cost-Effectiveness of Alternative Fuels for Shipping in Two GHG Pricing Mechanisms: Case Study of a 24,000 DWT Bulk Carrier. *Sustainability*. 17(13), 6001. DOI: <https://doi.org/10.3390/su17136001>
- [42] Faităr, C., Nedelcu, A.T., Buzbuchi, N., et al., 2018. Consideration of Energy Efficiency Operational Index Evaluation. *Journal of Physics Conference Series*. 1122, 12013. DOI: <https://doi.org/10.1088/1742-6596/1122/1/012013>
- [43] Christopher, M., 2000. The Agile Supply Chain: Competing in Volatile Markets. *Industrial Marketing Management*. 29(1), 37–44. DOI: [https://doi.org/10.1016/s0019-8501\(99\)00110-8](https://doi.org/10.1016/s0019-8501(99)00110-8)
- [44] Shekarian, M., Nooraie, S.V., Parast, M.M., 2019. An examination of the impact of flexibility and agility on mitigating supply chain disruptions. *International Journal of Production Economics*. 220, 107438. DOI: <https://doi.org/10.1016/j.prope.2019.107438>

- j.ijpe.2019.07.011
- [45] Shashi, S., Centobelli, P., Cerchione, R., et al., 2020. Agile supply chain management: Where did it come from and where will it go in the era of digital transformation? *Industrial Marketing Management*. 90, 324–345. DOI: <https://doi.org/10.1016/j.indmarman.2020.07.011>
- [46] Mackay, J., Munoz, A., Pepper, M., 2019. Conceptualising Redundancy and Flexibility Towards Supply Chain Robustness and Resilience. *Journal of Risk Research*. 23(12), 1541–1561. DOI: <https://doi.org/10.1080/13669877.2019.1694964>
- [47] Michel, S., Gerbaix, S., Bidan, M., 2023. Dimensions and Sub-Dimensions of Emergency Supply Chain Resilience: A Case Study of Médecins Sans Frontières Logistique During the COVID-19 Pandemic. *Supply Chain Management An International Journal*. 28(5), 939–953. DOI: <https://doi.org/10.1108/scm-07-2022-0278>
- [48] Riad, M., Naïmi, M., Okar, C., 2024. Enhancing Supply Chain Resilience Through Artificial Intelligence: Developing a Comprehensive Conceptual Framework for AI Implementation and Supply Chain Optimization. *Logistics*. 8(4), 111. DOI: <https://doi.org/10.3390/logistics8040111>
- [49] Constantinescu, M., 2024. Navigating the Turbulence: Unraveling the Nexus Between Transport Infrastructure, Conflict and Resilience. *Strategies XXI The Complex and Dynamic Nature of the Security Environment*. 177–188. DOI: <https://doi.org/10.53477/3045-2309-23-16>
- [50] Lotfi, M., Saghiri, S., 2017. Disentangling Resilience, Agility and Leanness. *Journal of Manufacturing Technology Management*. 29(1), 168–197. DOI: <https://doi.org/10.1108/jmtm-01-2017-0014>
- [51] Karamperidis, S., Valantis-Kanellos, N., 2022. Northern Sea Route as an Emerging Option for Global Transport Networks: A Policy Perspective. *WMU Journal of Maritime Affairs*. 21(4), 425–452. DOI: <https://doi.org/10.1007/s13437-022-00273-3>
- [52] Tran, T.T., Browne, T., Veitch, B., et al., 2023. Route optimization for vessels in ice: Investigating operational implications of the carbon intensity indicator regulation. *Marine Policy*. 158, 105858. DOI: <https://doi.org/10.1016/j.marpol.2023.105858>
- [53] Cook, A., Dawson, J., Howell, S., et al., 2024. Sea Ice Choke Points Reduce the Length of the Shipping Season in the Northwest Passage. *Communications Earth & Environment*. 5(1), 362. DOI: <https://doi.org/10.1038/s43247-024-01477-6>
- [54] Altay, N., Gunasekaran, A., Dubey, R., et al., 2018. Agility and Resilience as Antecedents of Supply Chain Performance under Moderating Effects of Organizational Culture within the Humanitarian Setting: A Dynamic Capability View. *Production Planning & Control*. 29(14), 1158–1174. DOI: <https://doi.org/10.1080/09537287.2018.1542174>
- [55] Ladeira, M.B., Oliveira, M.P.V. de Sousa, P.R. et al., 2021. Firm's Supply Chain Agility Enabling Resilience and Performance in Turmoil Times. *International Journal of Agile Systems and Management*. 14(2), 224–253. DOI: <https://doi.org/10.1504/ijasm.2021.118068>
- [56] Sturm, S., Hohenstein, N.-O., Birkel, H., et al., 2021. Empirical research on the relationships between demand- and supply-side risk management practices and their impact on business performance. *Supply Chain Management An International Journal*. 27(6), 742–761. DOI: <https://doi.org/10.1108/scm-08-2020-0403>
- [57] Zheng, J., Mao, C., Zhang, Q., 2023. Hybrid dynamic modelling and receding horizon speed optimization for liner shipping operations from schedule reliability and energy efficiency perspectives. *Frontiers in Marine Science*, 10. DOI: <https://doi.org/10.3389/fmars.2023.1095283>
- [58] Molloy, S., Franz, J., Rose, T., et al., 2023. Use of AI in real time vessel routing optimization and emissions prediction. In *Proceedings of the OCEANS 2023, Limerick, Ireland, 5–8 June 2023*; pp. 1–6. DOI: <https://doi.org/10.1109/oceanslimerick52467.2023.10244567>
- [59] Inman, R.A., Green, K.W., 2021. Environmental Uncertainty and Supply Chain Performance: The Effect of Agility. *Journal of Manufacturing Technology Management*. 33(2), 239–258. DOI: <https://doi.org/10.1108/jmtm-03-2021-0097>
- [60] Gu, Y., Wallace, S.W., Wang, X., 2018. Integrated Maritime Fuel Management with Stochastic Fuel Prices and New Emission Regulations. *Journal of the Operational Research Society*. 70(5), 707–725. DOI: <https://doi.org/10.1080/01605682.2017.1415649>
- [61] Pettit, T.J., Fiksel, J., Croxton, K.L., 2010. Ensuring supply chain resilience: Development of a conceptual framework. *Journal of Business Logistics*. 31(1), 1–21. DOI: <https://doi.org/10.1002/j.2158-1592.2010.tb00125.x>
- [62] Bogataj, M., Čuček, L., Žula, T., et al., 2018. Sustainable Synthesis and Optimization of Engi-

- neering Systems. WIT Transactions on the Built Environment. 175, 185–194. DOI: <https://doi.org/10.2495/hpsm180191>
- [63] Chen, W., Men, Y., Fuster, N., et al., 2024. Artificial Intelligence in Logistics Optimization with Sustainable Criteria: A Review. *Sustainability*. 16(21), 9145. DOI: <https://doi.org/10.3390/su16219145>
- [64] Fesobi, B.O., Fesobi, M.A., Ogungbeje, O., 2024. Implementing Agile Supply Chain Strategy for Improved Response to Market Volatility: A Systematic Literature Review. *South Florida Journal of Development*. 5(12). DOI: <https://doi.org/10.46932/sfjdv5n12-057>
- [65] Wang, H., Liu, Y., Fei, L., et al., 2023. Sustainable Maritime Transportation Operations with Emission Trading. *Journal of Marine Science and Engineering*. 11(9), 1647. DOI: <https://doi.org/10.3390/jmse11091647>
- [66] Dubey, R., 2019. Resilience and Agility: The Crucial Properties of Humanitarian Supply Chain. In: Ivanov, D., Dolgui, A., Sokolov, B. (eds.). *Handbook of Ripple Effects in the Supply Chain*. International Series in Operations Research & Management Science, vol 276. Springer: Cham, Switzerland. pp. 287–308. DOI: https://doi.org/10.1007/978-3-030-14302-2_14