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Sea-Ice-Informed Cargo Vessel Selection for Arctic Routes: Evidence from Daily Observations, 2016-2025

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Abstract: Arctic route choice cannot be separated from vessel capability because the same ice field imposes different operational consequences on open-water and ice-strengthened ships. This paper combines ten complete years of daily, 4 km MASAM2 sea-ice concentration observations (2016-2025) with a vessel-ranking and transit-reliability framework. Three broad corridors are compared: the Northern Sea Route (NSR), Northwest Passage (NWP), and Transpolar Route (TPR). Mean concentration, the 90th percentile, open-water share, and severe-ice share are extracted for each corridor. Five cargo-vessel concepts are evaluated by weighted TOPSIS, using ice capability, cargo efficiency, speed economy, fuel economy, capital-cost economy, and operational flexibility. Route-vessel performance is then tested through 10,000 Monte Carlo trials. During July-October, the NSR consistently presents lower ice exposure than the NWP, whereas the TPR remains dominated by high concentration. A Polar Class 6 bulk carrier obtains the highest TOPSIS score (0.759), narrowly ahead of a PC6 containership (0.735). The PC6 bulk carrier records a simulated NSR mean transit time of 22.19 d and a 95th percentile of 23.94 d. The evidence therefore supports a seasonal PC6 bulk service on the NSR for stable dry-bulk flows. The NWP is a secondary option, and the TPR should remain a strategic rather than routine commercial corridor under the observed conditions.

Keywords: Arctic shipping; Vessel selection; Sea-ice concentration; Northern Sea Route; TOPSIS; Monte Carlo simulation

1. Introduction

The commercial appeal of Arctic shipping is easy to describe but difficult to convert into a fleet decision. A shorter geographical connection between northern Europe and northeast Asia may reduce distance, yet an ice detour, an escort delay, or a conservative speed order can remove that advantage within a single voyage [1,3]. The problem is therefore not simply whether a northern corridor is shorter. It is whether a specified ship can move an economically useful cargo through the ice regime with an acceptable distribution of arrival times.

Previous accessibility studies show that declining summer ice can create new trans-Arctic opportunities, while also stressing substantial interannual variability [8,9]. Longer-term projections have even identified the possible emergence of central-ocean corridors for ice-strengthened vessels [10]. Such projections are useful for strategy, but an owner ordering a cargo ship faces a more immediate question: which vessel concept remains useful across the ice states actually observed during recent seasons?

Regulation reinforces this vessel-specific perspective. The Polar Code requires an assessment of the anticipated operating conditions, a Polar Ship Certificate, and a Polar Water Operational Manual for ships within its scope [7]. The POLARIS guidance similarly links ice regimes to ship capability rather than declaring a grid cell universally safe or unsafe [6]. Polar Class descriptions range from PC1 to PC7 and distinguish the severity and season of intended ice operation [5].

This study develops an observation-led screening method for cargo-vessel selection. It makes three contributions. First, it describes recent corridor-level ice exposure from a consistent daily dataset rather than from a single voyage or climatological month. Second, it ranks vessel concepts with criteria that retain both engineering capability and transport economics. Third, it subjects the ranking to stochastic transit tests and weight sensitivity. The output is a defensible short list, not an operational navigation plan.

2. Literature Review

2.1. Arctic accessibility and route choice

Model-based research has established that the NSR, NWP, and central Arctic do not open at the same rate or for the same ship. Smith and Stephenson (2013) demonstrated that vessel class changes the set of routes considered navigable [9]. Melia et al. (2016) found longer shipping seasons under continued sea-ice decline, but their results also retained large year-to-year differences [8]. The distinction matters commercially: average improvement does not guarantee a reliable window in a particular year.

The seasonal state of Arctic ice is changing across the annual cycle, but concentration alone does not describe ice thickness, ridging, drift, or pressure [11]. Recent corridor studies therefore use ship-class-dependent accessibility rather than an ice/no-ice dichotomy [8,9]. Even so, operational decisions remain conditional on daily forecasts and current ice charts. The present paper uses concentration as a consistent comparative exposure variable and explicitly avoids treating it as a complete ship-ice load model.

2.2. Commercial and vessel-selection considerations

Arctic economics are sensitive to ship size, cargo type, fuel price, escort fees, speed loss, and the probability of delay [1,3]. Faury and Cariou (2016) showed that the competitiveness of the NSR for tankers depends on the operating scenario rather than distance alone [1]. Lasserre (2014) reached a similarly cautious conclusion for container shipping [3]. Systematic reviews find that apparently favorable Arctic cases can reverse when ice-class premiums, seasonality, and uncertain

utilization are included [12]

A vessel choice is consequently multi-attribute. TOPSIS is suitable for an early design screen because it reports how close each alternative is to a constructed positive ideal while retaining trade-offs among criteria [4]. Its weakness is equally clear: a score reflects the chosen criteria, weights, and normalized engineering judgments. We therefore present both the score and its sensitivity, and we keep operational performance as a separate validation layer.

3. Data and Methods

3.1. Sea-ice dataset and analytical period

The local archive contains 168 monthly NetCDF files from July 2012 through June 2026. The primary sample is restricted to the ten complete calendar years from January 2016 to December 2025. The 2026 files are incomplete and are not used in the trend estimates. The source is MASAM2 Version 2 (G10005), a daily 4 km product that combines MASIE ice coverage with AMSR2 concentration information [2].

Version 2 assigns a minimum concentration of 40% where MASIE detects ice but the AMSR2 value is lower or unavailable [2]. This product behavior is important: the values are appropriate for repeatable route comparison, but marginal-ice concentration should not be interpreted as an independent high-resolution measurement at every pixel. Flagged land and missing cells were removed. The latitude-longitude fields and daily concentration arrays were sampled every twentieth grid point, yielding an approximate 80 km strategic grid. The dataset characteristics and analytical settings are summarized in Table 1.

Table 1. Dataset and analytical settings.

Item	Specification
Primary period	January 2016-December 2025
Temporal resolution	Daily fields stored in monthly NetCDF files
Native resolution	4 km x 4 km
Strategic sampling	Every twentieth x/y grid point
Navigation season	July-October
Corridors	NSR, NWP, and TPR proxy

3.2. Corridor definitions and ice metrics

The NSR corridor is represented by 70-82 degrees N and 25-180 degrees E. The NWP corridor covers 68-78 degrees N and 170 degrees W-55 degrees W. The TPR proxy comprises the high-latitude band from 80 to 89.5 degrees N. These broad masks support strategic comparison; they are not centerlines and do not encode charted depth, traffic separation, national permits, or local choke points.

For year y, month m, and route r, four statistics are calculated from valid cells: mean concentration, the 90th percentile concentration, the share with concentration at or below 15%, and the share at or above 70%. Annual navigation-season results are the unweighted mean of July through October. A route-risk index is used for the compatibility screen: R = 0.55 mean(SIC) + 0.30 P90(SIC) + 0.15 severe-ice share. The formula deliberately gives material weight to the upper tail.

3.3. Vessel alternatives and TOPSIS model

Five concepts are compared: a PC5 icebreaking multipurpose ship, PC6 bulk carrier, PC6 containership, PC7 general-cargo ship, and conventional open-water bulker. Polar Class labels are used as capability families, not as complete vessel specifications. Actual class notation requires design review and certification under the applicable rules [5]. The six evaluation criteria, their weights, and their interpretations are presented in Table 2.

Table 2. TOPSIS criteria and weights.

Criterion	Weight	Interpretation
Ice capability	0.32	Structural, propulsion, and operational margin in ice
Cargo efficiency	0.18	Useful cargo capacity and space utilization
Speed economy	0.14	Schedule performance in open water and light ice
Fuel economy	0.12	Relative transport-energy performance
Capital-cost economy	0.10	Ice-class and construction cost burden
Flexibility	0.14	Cargo, port, and shoulder-season versatility

The decision matrix is vector-normalized [4]. Each column is multiplied by its weight, after which positive and negative ideal points are identified. For alternative i, the closeness coefficient is C_i = D_i^-/(D_i^+ + D_i^-), where D_i^+ and D_i^- are Euclidean distances from the positive and negative ideals. Higher C_i indicates a more balanced concept within this screening model.

3.4. Monte Carlo validation

Transit reliability is estimated using 10,000 trials for every route-vessel combination. Corridor ice concentration is drawn from a truncated normal approximation fitted to the ten annual navigation-season values. Effective speed declines with concentration and with the mismatch between ice exposure and the alternative ice-capability score. Additional delay is activated above the capability threshold and an exponential disturbance with a mean of 0.6 d captures non-ice waiting. Scenario distances are 6,500 n mile for NSR, 7,200 n mile for NWP, and 5,600 n mile for TPR. These are controlled comparison parameters, not official distances for a specific port pair.

4. Results

4.1. Observed corridor contrast

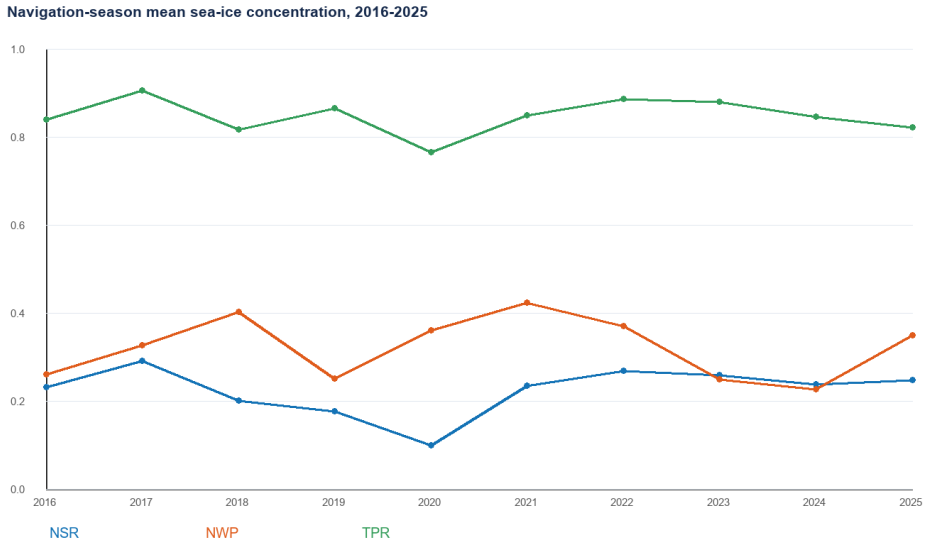


Fig. 1 July-October mean sea-ice concentration by corridor, 2016-2025.

As shown in Fig. 1, the ordering of sea-ice concentration across the three corridors is stable even though the annual values vary. The NSR usually records the lowest navigation-season concentration. NWP exposure is higher in most years and shows pronounced adverse seasons, while the TPR proxy stays close to heavy ice throughout the record. The 2020 NSR value is particularly low, but the rebound in later years cautions against extrapolating one favorable season into a permanent operating assumption.

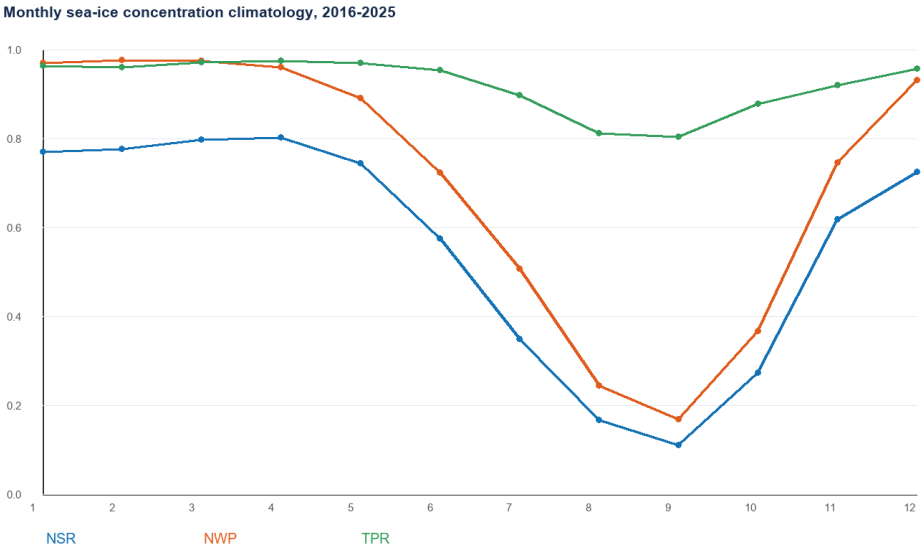


Fig. 2 Monthly sea-ice concentration climatology for 2016-2025.

As shown in Fig. 2, the monthly sea-ice concentration climatology indicates that ice exposure is lowest in late summer and early autumn. NSR concentration falls earlier and farther than NWP concentration. The TPR remains high even near its seasonal minimum. The result supports a dynamic July-October planning envelope for NSR service, with voyage authorization tied to current information rather than to a guaranteed opening date.

4.2. Vessel ranking

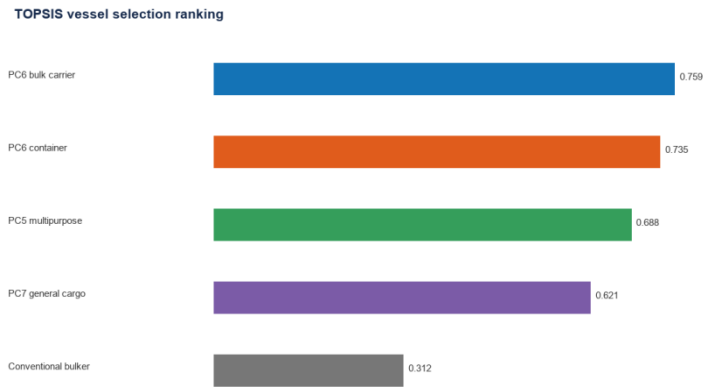


Fig. 3 Weighted TOPSIS scores for the five vessel concepts.

Table 3. Vessel-selection results.

Rank	Alternative	Score
1	PC6 bulk carrier	0.759
2	PC6 containership	0.735
3	PC5 icebreaking multipurpose ship	0.688
4	PC7 general-cargo ship	0.621
5	Conventional open-water bulker	0.312

As shown in Fig. 3 and Table 3, the PC6 bulk carrier ranks first because it combines strong ice capability with the highest cargo-efficiency score among the ice-strengthened alternatives. The PC6 containership is close behind; its speed and flexibility are attractive, but its cargo and fuel scores are slightly less favorable in the present bulk-oriented decision structure. The PC5 multipurpose concept offers the largest ice margin, yet the added capital and fuel burden prevents it from leading the balanced ranking. The conventional bulker is efficient in open water but loses most of that advantage once ice capability enters the model.

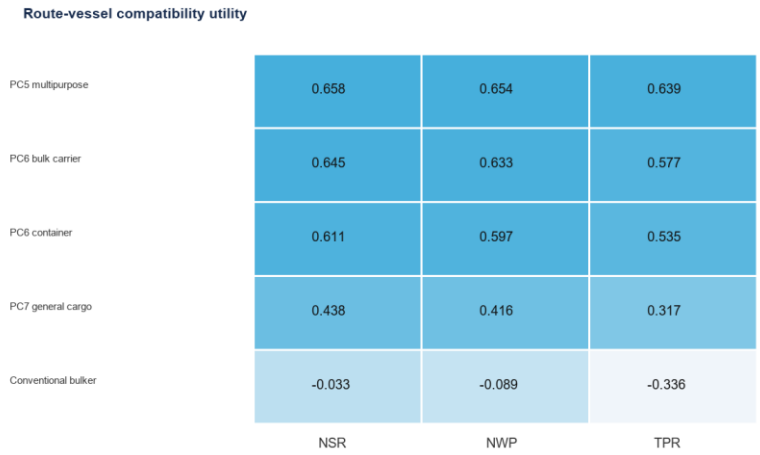


Fig. 4 Route-vessel compatibility utility after adjustment for observed ice exposure.

The compatibility matrix in Fig. 4 separates strategic ranking from route assignment. PC5 produces the highest route-adjusted utility because its capability is least penalized as exposure rises. PC6 bulk nevertheless retains the strongest economic-capability balance for NSR service. Negative utility for the conventional bulker on all corridors shows that low capital cost should not be mistaken for Arctic suitability.

4.3. Transit-time reliability

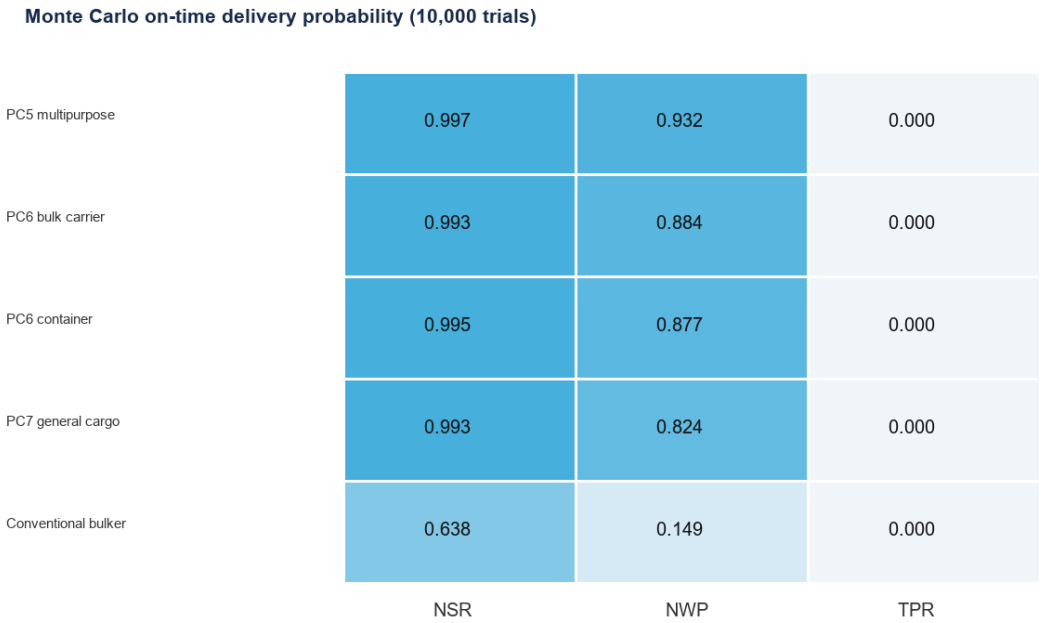


Fig. 5 On-time probability from 10,000 Monte Carlo trials per route-vessel combination.

Table 4. Simulated transit-time distributions.

Vessel	NSR mean/P95 (d)	NWP mean/P95 (d)	TPR mean/P95 (d)
PC5 multipurpose	22.77 / 24.49	26.83 / 29.18	34.95 / 38.52
PC6 bulk carrier	22.19 / 23.94	26.26 / 28.64	37.35 / 41.24
PC6 containership	22.20 / 23.89	26.29 / 28.71	37.86 / 41.82
PC7 general cargo	24.01 / 25.86	28.55 / 31.33	43.86 / 48.47
Conventional bulker	23.75 / 27.22	30.12 / 35.33	56.10 / 63.49

As reported in Table 4, the PC6 bulk carrier has an NSR mean transit time of 22.19 d and a 95th percentile of 23.94 d. Its simulated on-time probability is 0.993 for NSR and 0.884 for NWP (Fig. 5). The corresponding NWP decline demonstrates that a vessel recommendation cannot be transferred between corridors without modifying the service promise. The conventional bulker retains only 0.638 on-time probability on NSR and 0.149 on NWP. No alternative satisfies the study threshold on the TPR, which remains unsuitable for routine service in this historical experiment.

4.4. Sensitivity and route recommendation

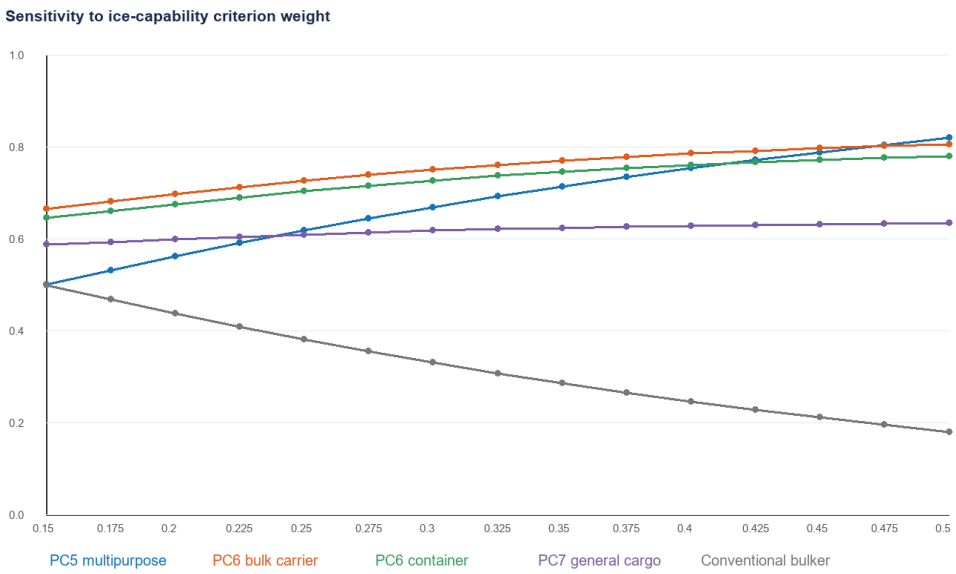


Fig. 6 Sensitivity of TOPSIS scores to the weight assigned to ice capability.

As shown in Fig. 6, increasing the ice-capability weight from 0.15 to 0.50 improves the PC5 position and further weakens the open-water bulker. The PC6 concepts remain competitive throughout most of the interval. The base recommendation is therefore not produced by a single narrow weight setting, although a company that gives overriding priority to independent ice capability would rationally prefer PC5.

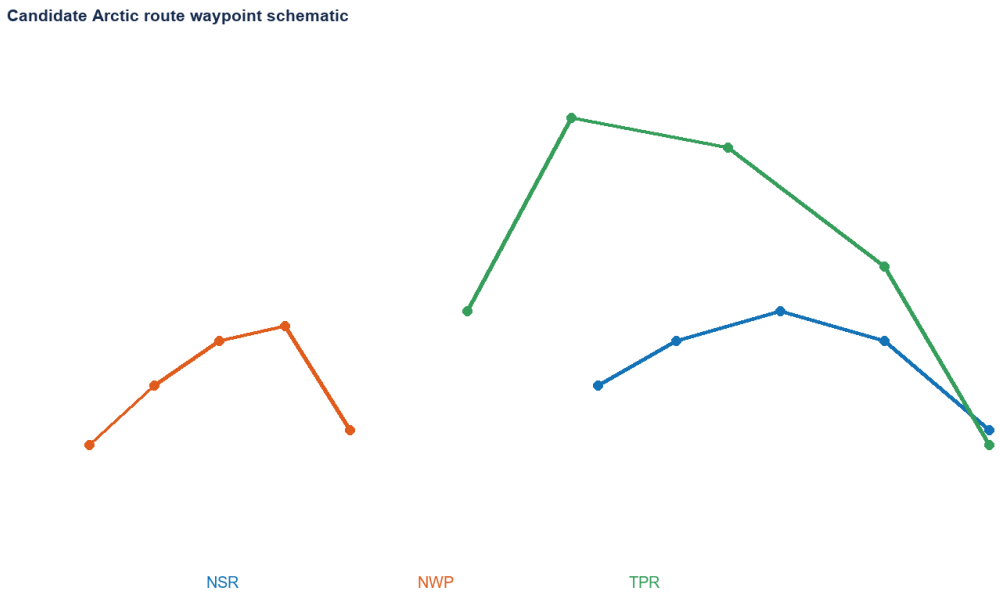


Fig. 7 Strategic waypoint schematic for the three candidate corridors; not for navigation.

Fig. 7 provides a schematic overview of the three candidate corridors for geographical context and is not intended for navigation. The recommended service is a PC6 bulk carrier on the NSR within a dynamically confirmed summer-autumn window. A PC6 containership is suitable when cargo value and schedule justify the higher service sensitivity. PC5 multipurpose tonnage is preferable for project cargo, shoulder-season work, or a policy that values additional ice margin. NWP remains a secondary corridor because of higher observed exposure and local archipelago constraints. TPR is retained only for long-range planning.

5. Discussion

The main result is not that PC6 is universally optimal. It is that a middle ice class can dominate when the cargo task rewards capacity and the selected corridor offers a recurring low-ice season. PC5 becomes more attractive as the voyage moves toward shoulder months or higher latitudes. Conversely, an open-water ship can appear attractive only if the operator assumes a reliably ice-free window; the ten-year record and simulation do not support that assumption for routine service.

The ranking also clarifies why Arctic service design differs by cargo market. Dry bulk can tolerate seasonal scheduling and can concentrate volume into a limited window. Container service places greater value on frequency and arrival consistency, so the NWP reduction in on-time performance is more damaging. This accords with earlier findings that distance savings alone do not guarantee commercial competitiveness (Lasserre, 2014; Faury and Cariou, 2016).

Several limitations bound the conclusions. Concentration does not include thickness, stage of development, ridging, pressure, drift, visibility, or wave-ice interaction. The strategic masks are wider than actual routes and do not resolve straits or bathymetry. Vessel criteria are relative engineering judgments, not shipyard quotations or class-approved performance curves. The Monte Carlo model uses simplified distributions and fixed comparison distances. Future work should replace the corridor masks with time-dependent least-cost paths, introduce ice thickness and age, and calibrate speed loss against AIS and full-scale trials.

Operational use requires a second decision layer. Before every voyage, the owner and master must evaluate current ice products, weather, daylight, chart quality, communications, search-and-rescue coverage, escort availability, permits, and the limits stated in the Polar Ship Certificate and Polar Water Operational Manual (IMO, 2017). The schematic in Fig. 7 must not be used as a navigational route in an ECDIS.

6. Conclusion

Ten complete years of daily MASAM2 observations show a clear strategic hierarchy among the examined corridors. During July-October, the NSR is the least ice-exposed option, the NWP is less reliable, and the central Arctic proxy remains dominated by heavy concentration. The vessel screen identifies the PC6 bulk carrier as the best balanced alternative, with a TOPSIS score of 0.759 and a simulated NSR transit time of 22.19 d on average. PC6 container tonnage is a credible second choice for valuable cargo, whereas PC5 multipurpose tonnage is justified when the operating policy requires a larger ice margin.

The practical recommendation is seasonal rather than absolute: deploy PC6 bulk capacity on the NSR only after a voyage-specific ice and regulatory assessment, retain a conventional route or waiting option, and avoid treating the TPR as a routine commercial corridor under conditions resembling 2016-2025. The framework can be updated each year without changing its decision logic, making it suitable for preliminary fleet planning and for comparing more detailed ship designs.

Acknowledgements

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