Icebreakers Route Planning

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Abstract. The vehicle routing problem (VRP) plays a critical role in modern logistics, particularly in challenging environments such as the Northern Sea Route. In such contexts, determining how to efficiently organize convoys consisting of icebreakers and accompanying vessels, as well as planning optimal routes using dynamic ice condition data, remains a key challenge. This study introduces a heuristic algorithm for icebreaker routing, enhanced by an interactive web-based service designed to support real-time decision-making and route optimization. The solution can be accessed via link: https://github.com/sttie/ldt-rosatom/tree/main

1. Problem Formalization

The objective is to coordinate nuclear icebreaker escorts for commercial vessels through regions with fluctuating ice conditions. Key features include:

- Independent movement of all vessels;
- Ice conditions and navigable paths changing over time and space;
- Vessel heterogeneity in ice class and speed;
- Dynamic convoy composition;
- Impassable areas even for escorted vessels [1];
- Dependence of convoy speed on the weakest ship's ice class and ice resistance.

These complexities preclude static routing models, demanding flexible and efficient routing strategies. The task involves synthesizing data from fixed route graphs, ice resistance grids, and schedule constraints, ensuring compliance with detailed rules on escort eligibility and convoy speed limitations.

2. Methodological Approach

We combined greedy heuristics with elements of optimization. A dynamic graph model was constructed from historical ice data, refined through interpolation and enriched with weight definitions reflecting ice class slowdowns and impassability.

To support fast rerouting, we used Floyd–Warshall preprocessing for all-pairs shortest paths, parameterized by vessel type and forecast intervals. This allowed route evaluation to adjust to real-time conditions, including speed degradation and seasonal ice shifts.

Relevant prior work includes the use of A* search on multi-layer flat graphs for similar navigation problems [1], and more general scheduling constraints in transport systems [2]. Pickup-and-delivery formulations [3, 4] and dynamic repositioning problems [5] inspired key structural choices in the model. None of existing solutions address problem with all listed conditions.

3. Greedy Scheduling Algorithm

The core logic relies on greedy per-step decision-making. At each simulation timestamp, the algorithm evaluates the state of all ships and icebreakers and determines convoy assignments. Possible actions for an icebreaker include:

- Continue escorting the current convoy;
- Divert to pick up a waiting ship if beneficial;
- Let a ship proceed independently if that is more efficient.

These decisions are driven by a score function balancing route time and waiting penalties:

$$\text{score} = w_1 \cdot \frac{\text{waiting\_time}}{\max \text{waiting\_time}} + w_2 \cdot \frac{\text{path}_{\text{current}}}{\text{path}_{\text{with\_pickup}}}$$

Threshold values and weights ($w_1 = 0.1$, $w_2 = 0.7$) were calibrated to favor beneficial diversions while maintaining momentum toward convoy destinations.

Sorting mechanisms prioritize icebreakers by proximity and convoy size, and ships by urgency and marginal gain. These heuristics proved effective across multiple traffic density scenarios.

4. Prioritization Strategy Analysis

A central focus of the research was analyzing how various prioritization strategies impact overall convoy efficiency. We experimented with weight ratios, scoring thresholds, and timing windows. Simulated results showed that:

- Delay minimization is sensitive to w_1/w_2 ratios;
- Overly aggressive rerouting causes fragmentation and inefficiencies;
- A calibrated threshold (e.g., 0.7) balances global vs. local gains;
- The worst-case path of the slowest vessel in a convoy governs feasibility.

Validation was performed through step-by-step consistency checks, ensuring no illegal transitions or premature arrivals occurred. Convoy compositions, deadlines, and vessel routes were traceable throughout simulation.

5. Web Interface and Visualization

To facilitate interaction with the system and improve result interpretation, a lightweight web application was implemented. The application allows users to upload data files (ice fields, vessel schedules, route graphs), configure convoy settings, and launch the scheduling engine directly from the browser. The result is visualized via an interactive map and a Gantt chart displaying the timeline of each convoy's journey.

Figure 1 shows a sample screenshot of the web interface, including convoy trajectories and planning schedule.

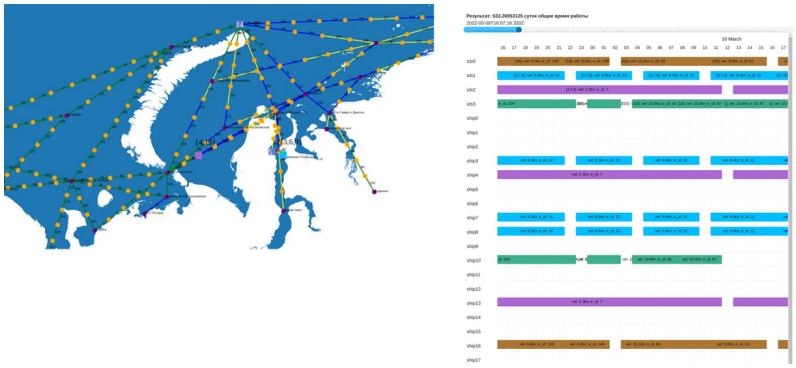

FIGURE 1. Mockup of the web interface with map and Gantt visualization

6. Conclusion

This work presents a functioning prototype system for icebreaker route planning along the NSR. Its core contribution lies in the dynamic prioritization logic that enables decentralized yet cooperative convoy routing. Unlike purely optimization-based approaches, our greedy strategy provides fast reactivity to changing environmental and operational inputs.

By fully aligning with the technical constraints of the hackathon—such as use of a fixed routing graph, dynamic weekly ice resistance maps, ice class constraints, and limited escort capacity—the system directly addresses the task of minimizing delivery time from request submission to arrival. Moreover, visual outputs, including Gantt charts and spatial trajectory animations, fulfill the requirement for interpretable results.

References

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