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Policy and Governance Simulation for Arctic Marine Routes

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ABSTRACT

This paper introduces PoGo (Policy and Governance), a simulation framework designed to assess the operational impacts of maritime policies on shipping, particularly for navigation in sea ice. By integrating ship performance models, metocean conditions, local community factors, regulations like the Polar Code and Carbon Intensity Indicator, and employing a route optimization algorithm, PoGo enables the evaluation of policy decisions and their effects on rights-holders and ship operators. The main elements of PoGo are described and the framework of the code is outlined. A case study on a cargo transportation service to Iqaluit is used to exemplify some the tool's features, focusing on vessel ice class, transportation season, fuel and crewing costs, carbon emissions, and voyage time. This application highlights how PoGo can be used as a strategic tool, identifying consequences of policy changes, navigation restrictions, and future regulation revisions. Effectively, the simulation framework can be used to assess the sensitivity of policy decisions in the context of Arctic shipping, and balance economic and other considerations.

KEY WORDS: Policy; Simulation; Routing; Shipping; Sea Ice

INTRODUCTION

PoGo is a ship routing algorithm. For a given voyage originating at a departure port and heading to a destination port at a specific time, PoGo will find the "best" route and speeds along the route in accordance with a user-defined value function and within constraints imposed by regulatory requirements. The value function in PoGo depends on a few basic expenses, including fuel costs and voyage costs (crewing and associated expenses). Elements of the value function are aggregated in terms of dollars.

To support an assessment of the value function, a ship performance model is used to estimate fuel consumption and the time required to complete a voyage. The main ingredients of the ship performance model are engineering models of ship resistance and propulsion in open water and in sea ice, from which the optimum speeds along a voyage can be determined, and from there the fuel consumption and voyage time can be estimated.

PoGo uses generalized models for resistance and propulsion. Holtrop's method (Holtrop 1984) is used to estimate ship resistance in open water. Resistance in ice is usually estimated using a modified version of Keinonen's method (Keinonen et al. 1996, Veber 2023). Both methods require ship-specific parameters, including principal particulars and hull form coefficients. Resistance in ice depends on ice conditions, so information on prevailing ice conditions must be provided to PoGo, normally in the form of ice charts in the region and at the time of the voyage. Similarly, added resistance in waves depends on met-ocean conditions, which requires met-ocean information relevant to the voyage time and place.

Powering is modeled using ship resistance and speed in combination with elements of efficiency. These elements are ship-specific so must be provided to PoGo for each ship. Fuel consumption is estimated based on the power required to travel at a particular speed as estimated by the resistance and propulsion models, in combination with technical specifications of fuel consumption for the engine(s) on the ship. Again, this is ship-specific.

Carbon emissions corresponding to fuel consumed are estimated using simple conversion factors that depend on the type of fuel being used. PoGo uses IMO guidance for this conversion (IMO, 2024).

In addition to finding an optimal route and speeds along the route for a given voyage, PoGo can do so within regulatory and other types of constraints. For example, PoGo incorporates the Polar Code's POLARIS regulation (IMO, 2016), MARPOL's Carbon Intensity Indicator (CII) regulation (IMO 2022), and a capability to operate within underwater radiated noise limitations. These regulatory and other constraints are incorporated in the ship performance model of PoGo.

POLARIS is used to identify limitations to navigation in sea ice and can be assessed using the ship's ice class and the prevailing ice conditions. If the POLARIS assessment indicates that the voyage can proceed through ice, the ship may continue, but it is still subject to other constraints, such as the availability of power.

CII is used to ensure compliance with emissions limitations. It requires ship specific and voyage specific information, including the cargo capacity of the ship, the type of fuel used, and the distance of the voyage. CII regulations include exemptions for some ship types, including ice-strengthened vessels, which requires that the relevant ship specific information be provided. CII is also formulated to become stricter over time.

Underwater radiated noise from ships is a concern in some local areas due to the disturbance of the marine ecosystem associated with such noise. PoGo incorporates a noise model (MacGillivray et al., 2022) that enables it to adhere to locally imposed operating guidelines or constraints related to underwater radiated noise. In effect, adherence to noise limitations might be achieved by re-routing around sensitive populations or slowing down to reduce the source noise sufficiently to meet specific noise thresholds.

Pathfinding and optimization in PoGo occur over a discretized grid world. The ice environment is modelled from a published sea ice chart, such as those from the Canadian Ice Service. Each grid cell represents open water, a defined ice regime, or land. Following a form of Dijkstra’s shortest path algorithm (Dijkstra, 2022), an agent (i.e., the vessel) iteratively explores the entire grid world and identifies an optimal route and speeds between defined departure and arrival points. At each grid cell, the agent incurs costs based on a defined rewards function. Elements of the rewards function are fuel costs and voyage costs.

The ship performance model is used to estimate resistance, powering, fuel consumption, and emissions in ice and open water as functions of vessel speed. Vessel speed is optimized to minimize the total cost incurred in a grid cell. The maximum attainable speed in a grid cell will be limited by the installed engine power, or potentially by imposed policy constraints, such as emissions limits per the CII regulation. These speed limits can impact the optimized speed in a grid cell. For example, in more severe ice conditions, it may be the installed engine power that limits the speed of the vessel. The agent then proceeds through the simulation by transiting to an adjacent grid cell and repeating the speed optimization process.

Ultimately, the output from a PoGo simulation is an optimized route and speeds as well as estimates of key performance indicators including total fuel consumption, voyage time, and fuel and crewing costs. At a more granular level, the optimized speed and costs are reported for each grid cell along the route. PoGo provides a means to investigate the operational implications that new or changing marine policies can have on ship operations.

METHODS

The route simulation process operates across four main stages. The first stage uses a graphical user interface where the user provides a set of scenario parameters. The scenario parameters fall into one of six categories: scene basics, ship performance particulars, scene files, CII regulation specifics, underwater radiated noise features, and the voyage cost setup.

The scene basics category asks for parameters like the simulation date, and departure and arrival ports. Ship performance particulars require the user to select an ice resistance modelling strategy and the corresponding ship particular parameters. The scene files category requires at least 3 file uploads: a discretized ice chart, its corresponding ice regime data, and a matching coordinate map, all of which can be made through the PoGo software. CII regulation specifics require inputs relevant to the calculation of a vessel's carbon output. Underwater radiated noise lets the user choose if the route optimization should include regions that are sensitive to a vessel's noise. Finally, the voyage cost category allows the user to modify the parameters that directly affect the path finding cost of the route optimization process.

Stage 2 is largely scenario initialization, beginning with the injection of departure and arrival coordinates into the user's provided ice chart(s). Each ice regime associated with an ice chart(s) is assessed for a risk value, based on the vessel's ice class, and regulation selection (POLARIS or AIRSS). The end of stage 2 initializes modules for stages 3 and 4.

Stage 3 sets up the ship performance model, essentially creating a lookup index to determine speed selection capabilities based on grid world conditions. The ship performance for a given grid world cell is determined by a combination of the underwater radiated noise effect, travel through sea ice effect, and added resistance in waves effect.

Stage 4 engages the Dijkstra route optimization. The ice chart(s) are navigated from the departure cell to the arrival cell, assessing each neighbor cell for cost. Given the vessel can successfully navigate from the departure point to the arrival point, a coordinate path is determined and plotted, alongside a results file that contains route specific information such as fuel consumption, duration, and distance.

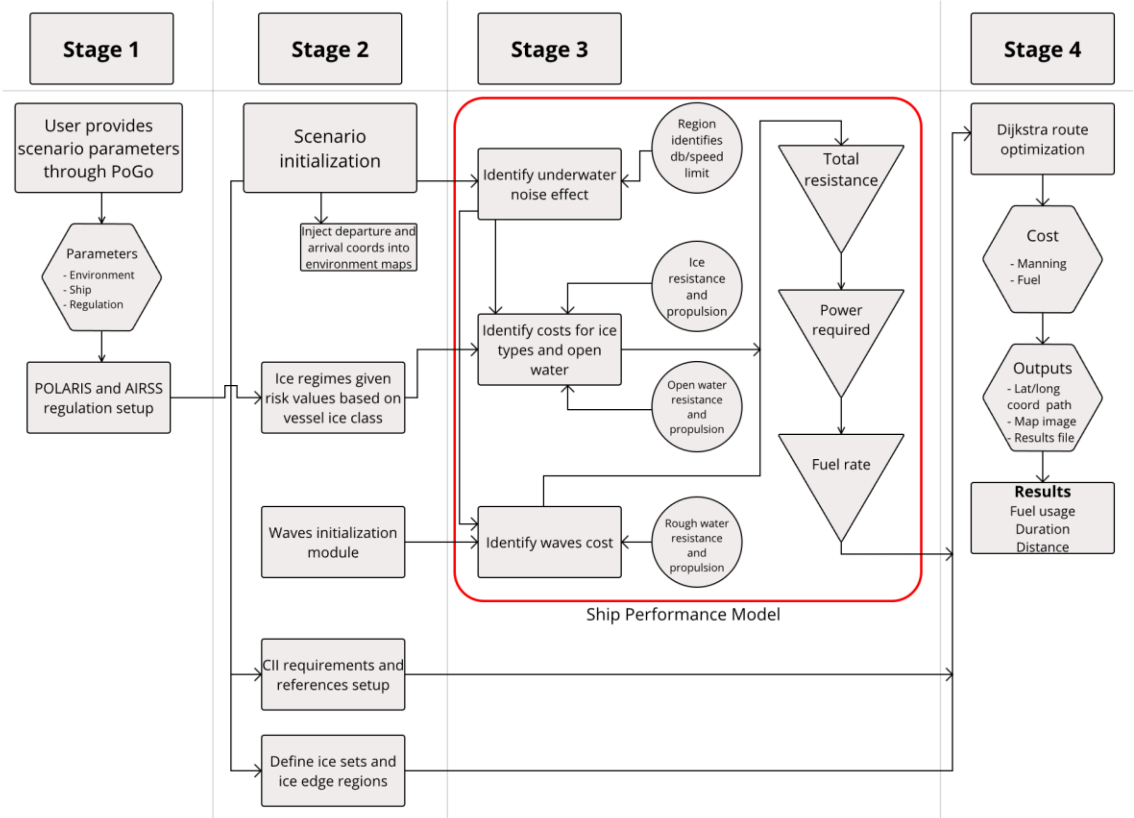

Figure 1. PoGo methods diagram

RESULTS

A case study scenario serves to demonstrate how PoGo works. Consider a general cargo marine transportation service from Quebec City in the Saint Lawrence River to Iqaluit in Frobisher Bay, Baffin Island. A ship loading at Quebec City would typically sail down the Saint Lawrence River to the Gulf of Saint Lawrence, go through the Strait of Belle Isle, then up the Labrador Sea and finally into Frobisher Bay, discharging at Iqaluit. Sea ice forms annually all along this route, with the duration of the navigation season depending both on actual ice conditions and the vessel's ice class. Navigation into Iqaluit for a typical ice strengthened cargo ship can proceed for about 8 months of the year, from July to February or March, before ice conditions prevent safe operations according to POLARIS. Given the typical ice conditions near Iqaluit, a Polar Class of PC 5 (or even PC 4) would be required for year-round access. Severe ice conditions in the Strait of Belle Isle, which constitutes a natural choke point for sea ice, can occasionally necessitate taking a longer route around the south coast of Newfoundland, into the Atlantic Ocean, and then up the Labrador Sea.

A hypothetical general cargo ship is used in the case study. The ship is 130 m long, has main engine power of 5500 kW, a nominal design speed of 15.5 knots in open water, and an ice class of IA. The price of fuel is assumed to be $600/tonne and crewing costs are approximately $16,000/day. These are the only expenses accounted for in the model.

In open water conditions, the optimum speed according to PoGo is 15 knots. The voyage from Quebec City to Iqaluit takes 104 hours, consumes 70 tonnes of fuel, and has a CII of 13.65, which is less than the required CII of 14.2 for this ship. These baseline voyage results are sensitive to changes in the cost structure. For example, a 25% decrease in manning costs results in a change in speed to 14 knots, a slightly longer voyage at 112 hours, 11% less fuel consumed, a lower CII score of 12, and a 16% decrease in total voyage costs. Similarly, a 25% increase in fuel costs also results in a slower speed of 14 knots and an 8% increase in total voyage costs. A 25% increase in manning costs results in a 15% increase in total voyage costs, but the optimum speed remains the same as the baseline case at 15 knots. Similarly, a 25% decrease in fuel costs results in a 9% decrease in total voyage costs, but no other changes to the baseline case.

We evaluated voyages of this vessel on this service for the ice conditions defined on weekly ice charts from the Canadian Ice Service for the year from the fall of 2023 to fall of 2024. That is, the route was evaluated weekly in accordance with the prevailing ice conditions as defined in the charts.

For example, the route taken through the conditions reported on the February 19, 2024 ice chart (Canadian Ice Service, 2025) is illustrated in Figure 2. The route is superimposed on the chart itself. On departure from Quebec City, the ship has to contend with relatively light ice conditions in the Saint Lawrence River, for example through regime R, characterized by 2/10^{ths} partial concentration of grey ice and 7/10^{ths} partial concentration of new ice. Ice conditions worsen at the Strait of Belle Isle as the ship heads into the Labrador Sea. For example, ice regime G has 5/10^{ths} partial concentration of thin first year ice and 5/10^{ths} grey-white ice. The ship clears ice off the coast of Labrador, but re-enters the ice farther north in the Labrador Sea before approaching Frobisher Bay, where it routes to avoid ice regime O, consisting of 5/10^{ths} medium first year ice and 5/10^{ths} thin first year ice, but nevertheless encounters the worst ice conditions of voyage.

Compared with the voyage in the baseline calm open water conditions, the voyage through the February 19 ice conditions takes 8% longer, uses 19% more fuel, and costs 12% more. The increases are due to the effects of sea ice. Likewise, the presence of sea ice along the route results in speed reductions, with more severe ice conditions leading to greater speed reductions. The nominal CII calculated for the voyage exceeds by far the CII limit for the vessel, but as there is an exemption applied to the CII for the part of the voyage in sea ice, the ship can still comply with the regulation.

The following week – February 26 – is the last one that the IA classed ship can navigate independently in the ice conditions approaching Iqaluit while maintaining compliance with POLARIS. Ice conditions in the subsequent ice chart (March 4) cannot be navigated by the IA ship. However, if the vessel was classed as IA Super, it would be capable of navigating into Iqaluit. Extending the navigation season by increasing the ice class comes with a corresponding increase in the fuel consumed and carbon emitted on the voyage, and a 24% increase in the total cost compared to the baseline.

Within the next week (March 11), POLARIS prohibits navigation into Iqaluit for the IA Super (and PC 7 and PC 6) class too. PC 5 is the lowest class that would enable navigation from March 11 to July, by which time the ice has retreated and open water conditions prevail again. Indeed, even PC 5 is not adequate for all of the ice conditions near Frobisher Bay: a PC 4 would be necessary for the conditions during one week (in June) of the year. In addition to the increase in capital costs associated with increasing the ice class to PC 5, extending the navigation season comes with additional voyage costs in terms of increased fuel consumption (e.g. up to 37% more than baseline), total expenses (up to 31% more than baseline), and significantly more carbon emissions, although the exemption attached to sailing in ice enables the vessel to comply with the CII regulation even while increasing total emissions.

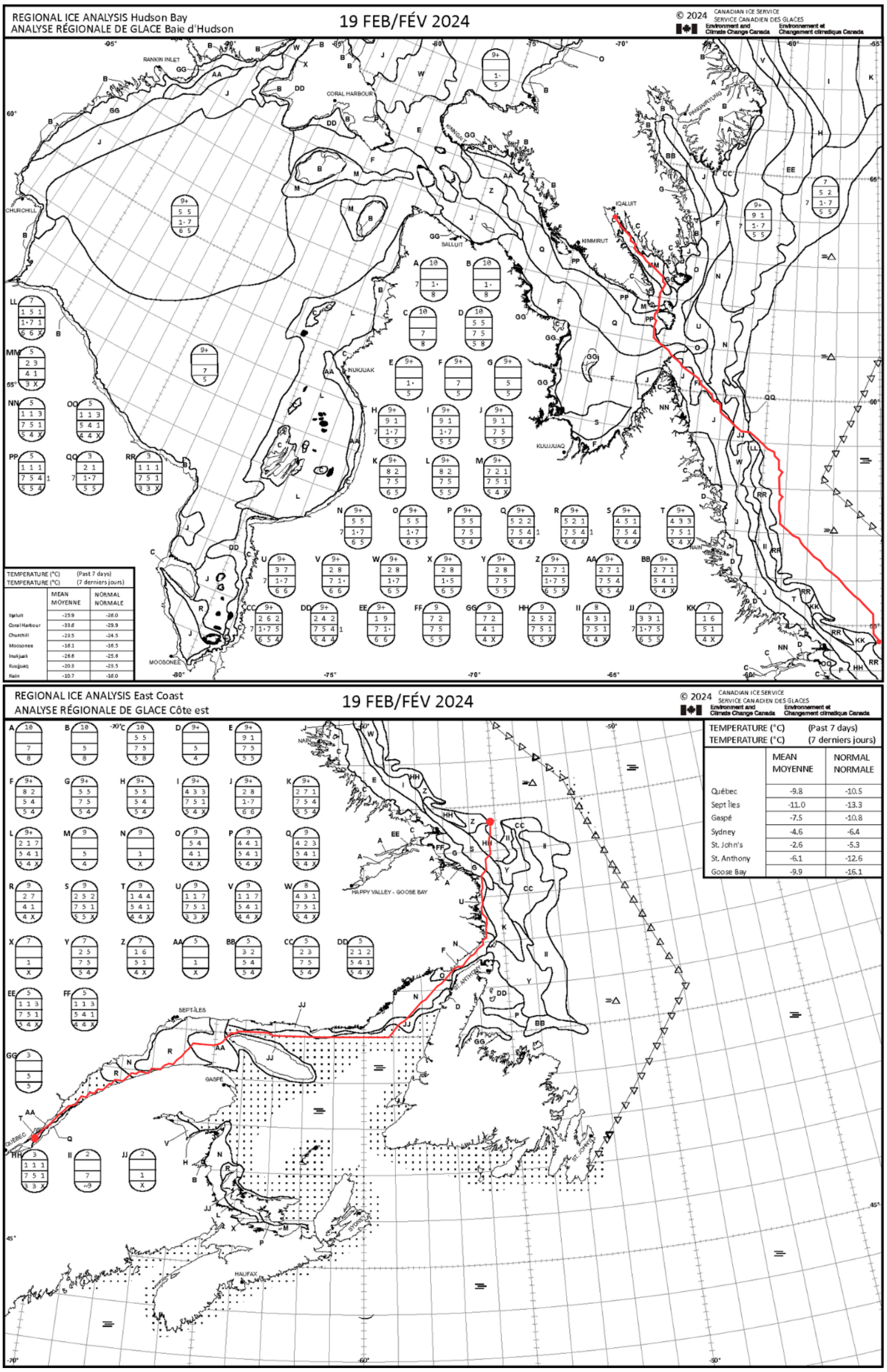

Figure 2. Ice chart for February 19, 2024, with route overlaid. (Ice chart used with Permission. © His Majesty the King in Right of Canada, as represented by the Minister of the Environment Canada)

CONCLUSIONS

PoGo is meant to serve as a simulation venue in which issues such as proposed policy changes or new regulations can be evaluated. It incorporates a ship performance model, met-ocean conditions between ports of departure and arrival, regulatory constraints, and a route optimization algorithm. As illustrated in the case study, it yields an optimal route, speeds along legs of the route, total fuel consumption, duration, carbon emissions, and costs. The effect of the POLARIS regulation was shown in the case study to restrict the navigation season in accordance with the combination of prevailing ice conditions and the IA class of the hypothetical ship we considered, so that the season for the particular service opened in July and closed in February. PoGo was also used to show that the navigation season could be prolonged (for example by increasing the ice class), but that extending the season came with significant incremental increases in costs, fuel consumption, carbon emissions, and voyage duration.

An example of a related issue that could be investigated by PoGo is the use of escort ice breaking to support commercial transportation. In the context of the hypothetical example shown in the case study scenario, there are two areas (Strait of Belle Isle, and approaches to Iqaluit via Frobisher Bay) where escort icebreaking might improve the voyage performance and perhaps extend the navigation season. The consequences of escort ice breaking could be evaluated on a voyage by voyage basis in terms of the performance indicators (fuel, carbon, costs, etc.) used in the case study example. By including the escort ship, the total system costs could be evaluated as well, rather than just the commercial ship performance.

Our case study did not account for the presence of glacial ice. Given the route used in the case study, glacial ice should not be neglected. In practice, seafarers might reduce speed voluntarily in conditions where glacial ice is known to occur, or is indeed shown on ice charts as occurring. PoGo does not yet model such decision-making heuristics, but we plan to do so. POLARIS was used to check to see if the ship was capable of entering specific ice conditions, thereby keeping the ship out of ice deemed to pose too high a risk to its structural integrity. In ice conditions that are deemed by POLARIS as permissible for a given ship, such as the IA class general cargo ship used in the case study, there are no additional operational restrictions, although it seems reasonable to contemplate speed limits, such as those recommended for “elevated risk” operations, to keep collisions between the ship and ice to within the energy bounds associated with some design load-response threshold. The implications of such speed limits could also be assessed using the PoGo framework.

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