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# The Northwest Passage: A simulation

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ABSTRACT

We model shipping through the Northwest Passage in northern Canada in order to see if reported recent ice thinning has made this route economic relative to the Panama Canal. Container shipping between Yokohama to New York and St. Johns, Newfoundland is simulated by VSLAM for the two routes using bluewater ships for the Panama Canal and identically sized Canadian Arctic Class 3 (CAC3) ships for the Northwest Passage. Each route is broken into a series of logical legs, and environmental conditions and wait times are assigned. Ice conditions are modeled from historical records. Average speed through the Northwest Passage shows little seasonal variation. Round trips per year are higher through the Northwest Passage. The required freight rate (RFR) to recover all costs including capital recovery is calculated. RFR is slightly lower for the St. Johns to Yokohama transit using the Northwest Passage, and higher for the New York to Yokohama route, as compared to the Panama Canal. Possible future thinning of Arctic ice would further improve the economics of the Northwest Passage.



## 1. Introduction

The fabled Northwest Passage was the goal of early European navigators: could the Far East be reached by going across North America, avoiding the long route through the difficult straits of Magellan? The answer was no: ice conditions were too difficult, slowing transport at best and destroying carriers at worst. Franklin and others taught the dangers of the passage, and the longer sea route, and later the Panama Canal, became the routes of choice.

Recently arctic ice has been thinning, an impact related to the warming of the Canadian north. Ships that can manage ice on a year round basis are available (Mulherin et al., 1994), but the critical question is whether on a commercial basis the Northwest Passage is competitive with the Panama Canal.

In this study we evaluate the relative economics of shipping through the Northwest Passage and shipping through the Panama Canal. We select two source ports on the east coast of North America, New York and St. Johns, Newfoundland, and one destination port, Yokohama, Japan. Two alternative paths through the Northwest Passage are considered.

Ocean transport involves uncertainty. For example, the traditional route from North America to Japan involves variable ship speed due to wind and wave conditions, and the passage through the Panama Canal involves a variable wait time. Ice conditions create far greater uncertainty in the Arctic rates of passage. We therefore develop models to simulate each route in this study. We use a commercial simulation software, VSLAM, and the BestFit and @RISK Excel add ins to develop stochastic models. We incorporate historical ice regime data on ice cover in the Canadian Arctic to prepare probabilistic ice regimes. We then estimate ship speed based on ice conditions. For the Panama Canal route we incorporate probabilistic

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models of wait time and variability in ship speed. Speed and distance are used to estimate total transit time and the required freight rate for economic shipping, thereby allowing an economic comparison of the alternatives.

## 2. Outline of methodology

The methodology of this study is composed of three parts: input modeling, system modeling, and analysis of the output.

The first step is definition of the key performance measure. For ocean transport alternatives, a common measure of performance is the required freight rate (RFR) (Stopford, 1997). Actual shipping rates depend on supply and demand, and can be above or below RFR; shipping rates may also reflect the commodity being carried, for example when containers of perishable food items are carried. The RFR is calculated by calculating, in turn, the annual cargo capacity of a potential route and the cost, including operating cost and capital recovery or lease cost, of each type of ship in the study. Annual cargo capacity in turn derives from the number of round trips per year and the ship's capacity/tonnage. The number of round trips per year in turn depends on speed, distance and port turnaround time, canal wait times, and downtime for maintenance over the course of a year. We first calculate the theoretical round trips per year based on full utilization of the ship, assuming no port delays or downtime due to lack of demand or extreme weather. To account for all other ship idle time we then adjust the theoretical round trips by applying a sailing productivity factor of 93% (hours sailing per hours available to sail, excluding port and repair time) resulting in an estimated 7200 h of open water sailing time for the bluewater ship (Corbett and Koehler, 2004) and 7095 h of open water plus ice sailing for the Arctic ship. Note that a ship making multiple port calls would have lower sailing hours; the relative cost of the two routes is not significantly affected by the number of port calls. Also note that the RFR calculated in this work excludes port charges and customs duties.

Ship speed depends on the environmental conditions and ship capability. For conventional ocean travel wind condition and resulting wave motion are the primary variable. These factors are reflected in a probability distribution of speed over open water for each type of ship.

For the Northwest Passage the primary impact of environment on ship speed is ice cover. To model the ice condition and its spatial and temporal variations we divided the Canadian Arctic route into nine legs and 50 weeks. The legs or the spatial grids for the model are depicted in Fig. 1. The spatial grid was not kept uniform through out the passage, but was assigned based on regions having contiguous environmental conditions. Historical data on ice regimes in the Canadian Arctic is used to develop probability distributions of ice for each leg of a route through the Northwest Passage; ice conditions are simulated for different times of year. The impact of ice on ship speed is estimated through an ice numeral that indicates the degree of difficulty; it is a function of both type of ship and thickness and type of ice. The ice numeral is correlated to speed.

Specific routes are defined through the Panama Canal and the Northwest Passage. The distances and safe depths for navigation were estimated from nautical charts and distance table provided by Canadian Hydrographic Service (2004) and National Imagery and Mapping Agency (2001). Conventional routes that use the canal are well defined. The Northwest Passage

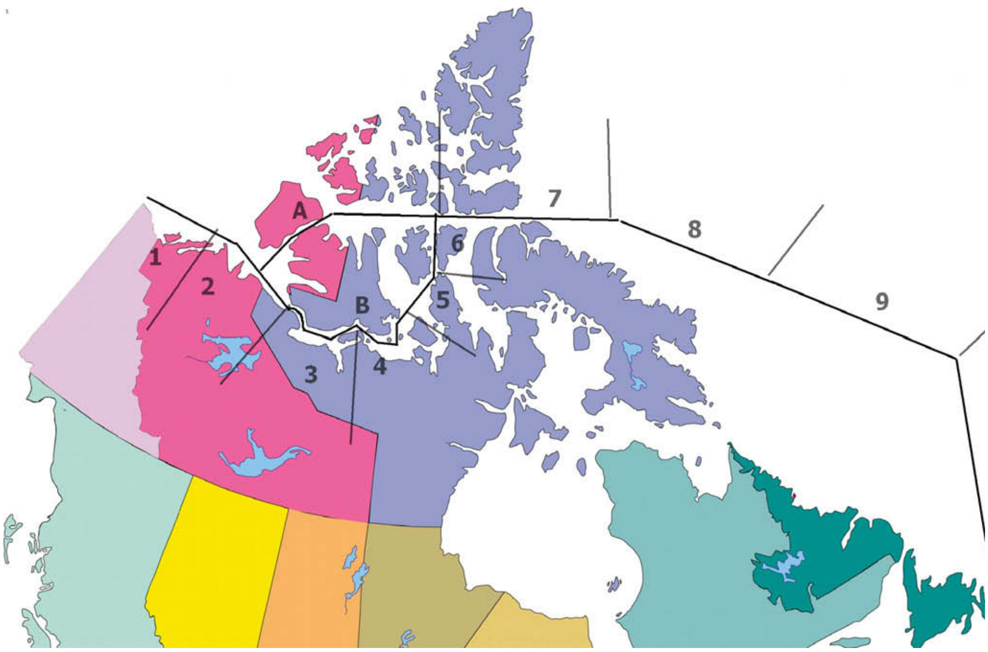


**Fig. 1.** Two alternate routes A&B and the nine legs.

has two alternative routes, and each was evaluated in this study. However, early analysis of the Viscount Melville Sound route (Alternative A in Fig. 1) indicated that it was essentially impassable to commercial cargo ships, even those with ice breaking capability, for well over half the year. Therefore, this route was dropped from the study. The Northwest Passage reduces total transit distance by 3500 nautical miles (33%) for St. Johns to Yokohama, and by 1650 nautical miles (17%) for New York to Yokohama.

Transit was simulated over an annual cycle for each type of ship. The simulation included loading and unloading time in port; direct return passage from Yokohama to North America was assumed. Starting at a given point, chosen arbitrarily as Yokohama on January 1, and proceeding back and forth through an entire year, transit time per trip, trips per year, and hence annual cargo capacity was calculated. The simulation experiment was run for 300 times; the average annual cargo capacity reflects the uncertainty in environmental conditions. Annual cargo capacity and the total cost of operation of each type of ship allow the calculation of the key performance indicator, required freight rate.

The simulation of the route through the Northwest Passage is the more complex of the two routes. Key elements of the methodology are illustrated in the flow chart in Fig. 2 and are discussed in further detail below.

## 3. Navigation through sea ice

Mulherin et al. (1999) carried out a sensitivity analysis of the environmental variables that affect the transit speed of a ship in the Arctic and concluded that ice conditions were the dominant factor, responsible for 2/3 of the resultant vessel speed. In this study we focus on Arctic ice conditions alone as the cause of variation in transit time. A data base of ice conditions based on historical data from 1999 through 2003 was drawn from the Canadian ice chart archives of Environment Canada (Canadian Ice Service, 2004). Regional ice charts are issued monthly from December to April, biweekly in May, and weekly from June through November. A total of 310 charts were analyzed.

Ice conditions present in a given region at a particular time are called the ice regime. The Canadian Arctic Ice Regime Shipping System Standards (AIRSS) (Transport Canada, 1998) defines an ice regime as "a geographically continuous area having a relatively consistent distribution of any mix of ice types including open waters during a particular time". The Canadian ice charts show the ice regimes within the region; the 310 charts analyzed in this study contained 2366 regimes along the chosen routes. Each regime has a code (called an ICE EGG) assigned to it that describes the following properties:

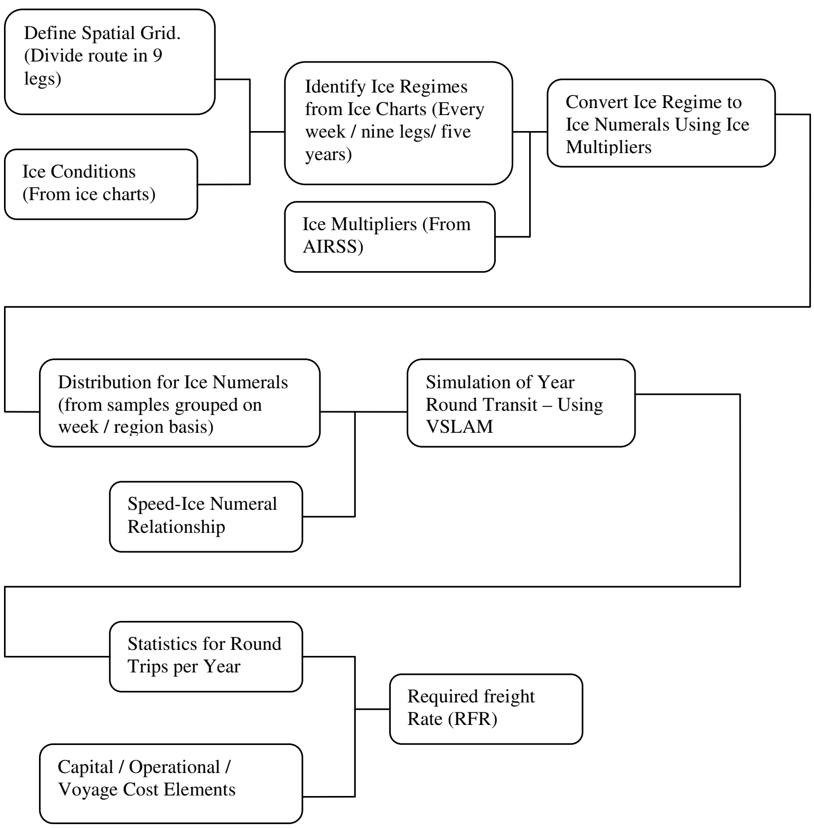


**Fig. 2.** Flow chart of simulation of ship passage through the Northwest Passage.

- Age and thickness, i.e., stage of development of ice, represented by a number called the "ice type".
- Total concentration, expressed as a fraction of the sea covered by ice, expressed in tenths.
- Partial concentration of a particular ice type, expressed for the three thickest ice types in the regime, expressed in tenths.
- The form (floe size) of each ice type.

Each of these factors affects a ship's performance in breaking through ice. Old thick ice presents the highest degree of difficulty for ice breaking and ship transit, with glacial ice in an iceberg being an extreme. Floe size affects routing decisions: small floes of thick ice can be circumnavigated, while larger floes must be transited. A further property of an ice field is its internal pressure, which can arise from wind forcing the ice against a landmass or from constrained expansion of the ice during its formation (Canadian Coast Guard, 1999). Ice pressure is second only to collision with glacial ice as a hazard to ships. Note, however, that ice charts do not record ice pressure; the impact of this on the model is discussed below.

The ice data, characterized by the EGG code, is analyzed by frequency for a given geographical location in the Northwest Passage, and then related to the ship's speed through an AIRSS algorithm (Transport Canada, 1998). The algorithm develops an ice numeral based on two inputs: the vessel's type and the ice condition. The AIRSS algorithm uses a matrix of multipliers and computes an overall ice numeral based on the concentration of each ice type in a regime and the ship's class. A previous study by Mulherin et al. (1999), treated concentration and thickness as independently occurring variables and predicted ice regimes from Monte Carlo samples for these parameters. The AIRSS algorithm ice numeral is a single integer variable which accounts for concentration, age, thickness of the ice type and the ship type. The AIRSS matrix uses the Canadian classification for rating ships designed for ice management, Canadian Arctic Class (CAC) designation, with CAC1 being the strongest ship and CAC4 being the weakest.

AIRSS calls for reducing the ice multiplier values by one if the concentration of ice exceeds 60% and 30% of that ice is ridged (Transport Canada, 1998), indicating the occurrence of ice pressure. However, the historical ice data from Environment Canada (Canadian Ice Service, 2004) only indicates ridging and does not quantify it. Mulherin et al. (1999) linked ice pressure to concentration but assumed that a 100% concentration of ice is required for this to occur. Note, however, that even a concentration of 100% does not necessarily imply high ice pressure. In the initial model we ignore the impact of ice pressure on ice numeral; a future refinement would be to include a probability of ice pressure, say 50%, when a high concentration of ice occurs, especially in the area of Lancaster Sound and the Coastal Straits which have been identified as being prone to high pressure ice (Canadian Hydrographic Service, 1985, 1994a,b; Canadian Coast Guard, 1999).

Despite floe size being a significant factor in affecting a ship's progress, it was not factored into the model, because if commercial shipping emerges in the Northwest Passage we assume that advanced remote sensing technology would enable routing of ships to avoid most direct encounters with thick ice floes.

One additional limitation of the ice modeling in the study is that decadal variations in sea ice would not be observed due to the limited duration of the data set. If commercial shipping becomes viable in the Arctic ice data collection and analysis will be extended.

## 4. Ship selection

The dimensions and capacities of ships transiting the Panama Canal are determined by the size of the locks. For this study we selected a 20 knot transit speed suitable for higher value merchandise typically carried in containers. To eliminate a bias based on economy of scale, identical ship size and open sea speed were chosen for the Northwest Passage route. Based on an early analysis we chose CAC3 ships due to the slow speed of CAC4 ships in ice conditions and their vulnerability to ice pressure.

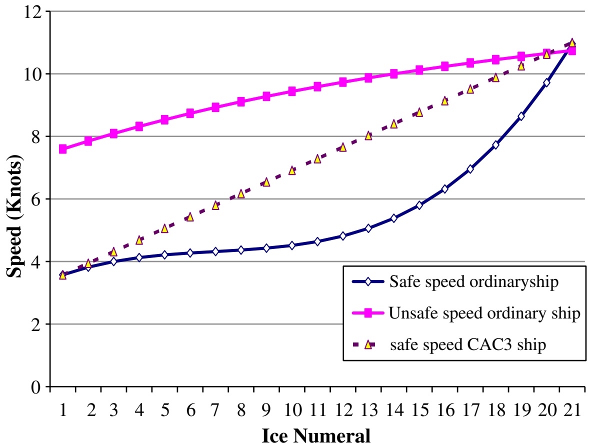


**Fig. 3.** Ship speed as a function of ice numeral.

The ice numeral and ship type are used to calculate a speed through ice. Numerous field validation studies of AIRSS were conducted by the Canadian Coast Guard (Lapp et al., 1986; McCallum, 1996). McCallum (1996) analyzed this data and proposed two polynomial fits, one for safe speed and the other for speeds leading to ice damage. However, these curves were for weaker class ships (i.e., below a CAC rating) with a design speed of 11 Knots. As no transit data exists for sturdier CAC3 ship we assumed that the speed curve for this vessel will lay between the safe and unsafe curve for the weaker ship at an equivalent power rating. The relationship is shown in Fig. 3; the data for the ordinary ship is from McCallum (1996).

A speed curve was derived for a more powerful 20 knot CAC3 ship by scaling up based on an assumed ship power of 50 MW vs. 12 MW for the 11 knot ship. Using the rule that speed is related to $(\text{power})^{0.33}$, this gives a design speed of 20 knots. This leads to the relation $y = 0.371 * x + 3.573$ for a CAC3 vessel designed for a speed of 11 knots and $y = 0.70 * x + 6.000$ for a CAC vessel designed for a speed of 20 knots, where $y$ is the safe speed and $x$ is the ice numeral.

## 5. Developing the model

The simulation software VSLAM was used for modeling the transportation systems. A discrete-event approach was used, in which changes occur only at event times and the system's state remains constant between events (Pritsker and O'Reilly, 1999). A dynamic portrayal of the system is obtained by advancing the simulation time from one event to the next by following the network paths or predefined constraints. The status variables are examined only at the event times.

For this study the route was divided into a number of legs ending/beginning at way points represented in the model as nodes. The distance between the way points can be viewed as the spatial grid for the model. Mulherin et al. (1999) chose a spatial grid representing 8 h sailing by a 17 knots ship. They then modified it to 2 h to check the impact of suddenly changing ice conditions. However, no significant change in simulation output was noticed. Hence, in choosing way points in this study primary consideration was given to including areas with similar ice conditions as one leg. For example, the whole of the Amundsen Gulf experiences unique ice conditions due to the presence of the Bathurst Polynya. Hence, the Amundsen Gulf was modeled as one single leg.

The ship was made to sail from one node to another with a speed assigned at the start node based on an ice numeral or open water speed sampled stochastically. The speed was assumed to be constant between nodes. Once the ship reached the next node, another assignment of speed was made depending on the ice condition prevalent at that time and the place where the node was located, or for open water on a new stochastic sampling of probable speed, thus simulating the spatial as well as the temporal advance of the ship.

A number of simplifying assumptions were made to make the model manageable.

- The environmental condition during one leg is independent of its preceding or following state. This could result in a scenario where an open water condition may be followed by a state of consolidated multi-year ice. However, this phenomenon will not affect the system's overall performance as the results reflect statistical values.
- If an ice numeral less than 0 and greater than or equal to $-5$ occurred, an ice breaker was used. The ice breaker was assumed to be instantly available; thereafter the speed was assigned at 5 knots for the rest of the leg, and the cost of the icebreaker was added to the voyage cost.
- If ice numeral values below $-5$ occurred, the vessel was assumed to be beset in ice. Beset vessels were kept beset for 168 h, or one week, and then sent back to the start of the leg. A count of such occurrences was taken.
- The legs were assumed to be direction-independent.
- The average deployment of a polar ship was assumed to 350 days per year, with 15 days for dry docking, amounting to 50 weeks or 8400 h of earning days. Earning days were considered to be on hire days, which include sailing as well as port stays for cargo work. The average deployment of a bluewater ship was assumed to be 360 days, with 5 days for dry docking. The higher maintenance time for polar ships accounts for the additional time spent on repairing ice damage.
- The speed in open water was assumed to be triangularly distributed with the design speed (the continuously rated speed) as the maximum and mode value, and the minimum value being 15% less than that of the continuous speed. This assumption was made to account for the reduction due to the vagaries of the wind and sea.

We recorded round trips per year, total distance, time in ice, time in open water, time in port, canal transit time, beset days and repair days. Three hundred runs, sufficient for the simulation to reach steady stage, were used to generate a statistical distribution of results. In order to calculate required freight rate, ship cost data were drawn from industry sources (Nagarajan, 2007; Panama Canal, 2004). Details of the modeling, including the use of BestFit to fit data, the use of a VSLAM ARRAY statement to model ice transit, and the spread sheet simulation for economic analysis are discussed in the Appendix.

## 6. Results

One surprising result from the simulation is that monthly average speeds for a CAC3 ship show little variation with season: monthly average speed in September is 18.4 knots, and in February is 18.2 knots. Table 1 shows the theoretical maximum round trips per year. A ship using the Northwest Passage can make 38% more trips per year on the St. Johns to Yokohama route, and 13% on the New York to Yokohama route.

**Table 1**
Statistics for theoretical maximum round trips per year for a 20 knot container ship

| Route | Transit | Round trips/year | |
|---|---|---|---|
| | | Mean | Standard deviation |
| Arctic | Yokahama–New York | 8.52 | 0.11 |
| Panama | Yokahama–New York | 7.55 | 0.017 |
| Arctic | Yokahama–St. Johns | 9.74 | 0.13 |
| Panama | Yokahama–St. Johns | 7.08 | 0.016 |

Since the capacity of the ships is identical, it is clear that at a constant freight rate the route through the Northwest Passage will generate more revenue than through the Panama Canal. However, a CAC3 ship is more expensive than a bluewater ship, and the key performance measure is the rate required to return capital and operating costs on each ship.

Data on transits per year can be combined with capital and operating cost data to calculate an RFR that covers voyage and operating costs and provides the ship owner with a return on capital. We illustrate this procedure here, using the cost data from Table 2. Note, however, that there is a lack of historical data on which to base cost estimates for the Northwest Passage route. No container ship conforming to CAC3 specifications has ever been built, and hence the capital cost premium relative to a bluewater ship, fuel consumption and insurance premiums from Table 2 have a very high degree of uncertainty. As interest in the Northwest Passage grows the uncertainty in cost data can be reduced by advancing the design of CAC3 commercial ships.

Table 3 shows the calculated RFR given the input data of Table 2. The higher cost of the CAC3 ship gives a higher RFR for the Northwest Passage route from New York to Yokohama despite the higher number of round trips per year on that route. For the St. Johns to Yokohama route the RFR is lower for the Northwest Passage: there is a slight economic advantage to using the Northwest Passage for year round transit. However, the estimated transit time is based on historical ice data from the period 1999–2003. As Arctic ice continues to thin (Comiso, 2002; Overland and Wang, 2007) the savings in RFR will increase.

## 7. Discussion

This simulation study indicates that for ice conditions in the Canadian Arctic for the period 1999 through 2003 use of the Northwest Passage is economically favored over the traditional route through the Panama Canal for ships sailing between St. Johns and Yokohama. In this study the size of ship was held constant, so none of the benefit cited in Table 2 for using the Northwest Passage vs. the Panama Canal arises from the potential to use a larger ship through the Northwest Passage. Hence, even larger benefit might arise from a larger CAC3 ship than can fit through the Panama Canal.

**Table 2**
Factors used in cost estimate

| Cost elements | Arctic | Panama |
|---|---|---|
| Capital cost (million $) (30% premium for Arctic ship)[a] | 67.6 | 52 |
| Ship sailing productivity | 93% | 93% |
| Amortization rate | 9% | 9% |
| Amortization period (years) | 25 | 25 |
| Management fee (million $/year)[b] | 2 | 1.65 |
| Dry dock cost (million $/year)[c] | 0.8 | 0.32 |
| Repair time (days per year) | 13 | 5 |
| Steel work cost ($/ton)[d] | 1500 | |
| Steel quantity (tons)[d] | 175 | 0.00 |
| H&M insurance premium (million $/year)[e] | 0.375 | 0.25 |
| P&I insurance premium (million $/year)[f] | 0.2625 | 0.175 |
| Bunker price ($/ton)[g] | 500 | 500 |
| Unit price lube oil ($/l)[h] | 1.85 | 1.85 |
| Specific fuel consumption (g/kW h)[h] | 165.5 | 165.5 |
| Average daily fuel consumption, New York transit[i] (ton/day) | 124,0 | 82.6 |
| Average daily fuel consumption, St. Johns transit[i] (ton/day) | 130.8 | 82.6 |
| Specific lube oil consumption (g/kW h)[h] | 1 | 1 |

[a] Nagarajan (2007).
[b] Nagarajan (2007). Additional fees due to additional staffing for Arctic route: ice navigator, additional engineer, four additional crew, additional spares for second propulsion train.
[c] Nagarajan (2007). Dry docking cost estimated at one dry dock per year for Arctic ship and two dry docks every five years for a bluewater ship.
[d] Nagarajan (2007). Steel work estimated every year for Arctic ship to repair ice damages; no steel work for bluewater ship.
[e] Nagarajan (2007). H&M (Hull&Machinery) insurance covers damages to hull and machinery and pollution arising there from.
[f] Nagarajan (2007).
[g] Bunker World (2008).
[h] MAN B & W (2004) and Wartsila Diesel (2004).
[i] Open water power demand from MAN B and W (2004), modified for two engine operation when ship is in ice.

**Table 3**
Calculated required freight rate for 9% return on capital

| Route | RFR ($/TEU) | |
|---|---|---|
| | Yokohama–New York | Yokohama–St. John's |
| Panama | 541 | 576 |
| Arctic | 625 | 563 |

The difference, $13 per TEU, is not compelling given the uncertainty and risk associated with the Northwest Passage. However, the thinning and shrinking of Arctic ice has been continuing. Thinner ice reduces the cost of the Northwest Passage by two immediate impacts: average ship speed increases, given yet more round trips per year, and fuel consumption per trip decreases. At $500 per ton for bunker fuel and more than 7000 sailing hours almost 2/3 of the RFR is for fuel. Fuel usage on the Northwest Passage is higher than through the Panama Canal despite the shorter distance, because of the higher power required for ice breaking. Even further thinning of Arctic ice would reduce the requirement for ship class from CAC3 to CAC4, reducing the capital cost of the ship as well as transit time and fuel usage.

Bunker price has shown a wide variation in recent years, as has crude oil price. For the ice conditions in this model fuel consumption is higher through the Northwest Passage, and a rise in bunker price to $650 per ton makes the Panama Canal route more economic from St. Johns to Yokohama.

Hence continuing to model the Northwest Passage is warranted, incorporating ongoing data on ice thickness (and hence ship speed and fuel consumption for the Northwest Passage route) and improved cost estimates for the capital and operating costs of ice capable ships. In addition, the model itself can be enhanced by collecting data to predict ice pressure and searching for decadal variations in ice conditions. The model can also be fine tuned by deriving an experimental and mechanistic correlation of ship's speed and ice numeral.

## 8. Conclusions

Several conclusions emerge from this study. First, simulation can be a valuable tool for analyzing alternative shipping routes when sufficient environmental data is available to predict the impact of factors such as ice. Second, a simulation study of shipping through the Northwest Passage vs. the Panama Canal indicates that average ship transit time through ice shows little seasonal variation, and more round trips per year can be completed for both a St. Johns, Newfoundland to Yokohama route (33% reduction in distance) and New York to Yokohama route (17% reduction in distance). Third, the model predicts a lower required freight rate for the Northwest Passage route from St. Johns to Yokohama but not from New York to Yokohama because for the latter the increase in number of round trips per year is more than offset by an increase in shipping cost. Fourth, continued thinning of Arctic ice will further reduce the cost relative to a Panama Canal route by three factors: faster transit time, lower fuel usage, and less capital investment for a suitable Arctic class ship.

## Acknowledgements

This work was first presented at the Winter Simulation Conference, 2006 in Monterey, California. The authors acknowledge the contribution of M.S. Nagarajan, General Manager (Operations) of Fleet Management Ltd., Hong Kong, a ship management company managing over 150 ocean going ships, for sharing proprietary cost information without which the modeling the cost data would not have been possible, and the financial support of the Poole Family through the Poole Chair in Management for Engineers.

## Appendix

A curve fitting procedure and the transit and economic model are described in detail.

Fitting of the probability distribution function (PDF) to the ice numeral data, was carried out by BestFit an Excel add in. BestFit ranks the fitted distributions according to various goodness of fit tests, the probability–probability (P–P) plots, quantile–quantile (Q–Q) plots, graphical comparison with the histogram for the data superimposed on the distribution curve, and comparison statistics for the distributions. The best distribution was selected by considering all these factors. Certain decision rules employed for reducing subjectivity are discussed below.

- Even if the fit statistics were in agreement, beta general was used if the sample had only two values. This kind of sample with ice numerals of 17 and 20 was encountered many times. The samples were the result of a correction applied to an open water regime whenever small icebergs were present. This correction was meant to account for the precautionary reduction in speed while sailing in such water.
- In case of a highly skewed sample, beta general or triangular distribution was preferred over the recommendation of the fit statistics.

- For a CAC3 ship the ice numerals range from 20 to (−)10, representing open water and consolidated multi-year ice, respectively. However, the range of the fitted distribution was not restricted to these limits, as doing so would have resulted in fewer choices of distributions. An ice numeral greater than 20 and less than −10 does not make any sense as far the physical system is concerned. To account for a few ice numerals outside the chosen range, provision was made in the system model to route them out of the network and to keep a count of such occurrences.
- Poor fitting was observed in most cases. Hence, emphasis was on visual selection rather than on relying on fit tests. As a rule of thumb for visual fits, the middle portion of a distribution was assumed to represent the performance expectation and the tail the risk expectation and the emphasis was on the conformity of the sample to the middle portion of the distribution curve. A total of 144 distributions were fitted to the whole data.

The transit was modeled by VSLAM. The VSLAM (Visual SLAM) is a simulation software marketed by Symix Systems Inc. The VSLAM framework facilitates combination of all the alternate world views used in simulation practice namely; event orientation, activity scanning orientation, process orientation, and continuous or discrete modeling. The language along with its support tool AWESIM allows the modeler to use graphic symbols to represent complex problems and is especially useful for problems which can be visualized as a flow network. The network in VSLAM consists of nodes and activities or flow paths connecting these nodes. At the nodes the attributes of the succeeding activity is defined and the entity proceeds to next nodes based on the new definition which could be the duration of the activity or a flow path sequence. For example a city road network could be modeled in VSLAM with the nodes representing the lights or junctions and the link between the junctions represented by an activity. A red light could be a node and a green another node, with the time delay between light changes represented by an activity. The activity duration of the link could depend on variables like the gradient of the road, the traffic density etc. Some of these variables like traffic density are time dependent while others like gradient are constant. In our case we chose the ship as the entity and she was made to sail from one node to another. The nodes in our model were end of a week or a leg, where checks for the ice conditions were made. The duration of an activity connecting two nodes depends on the distance between the nodes and the speed both values being assigned at the start node. Time is considered the independent variable. The dependent variable is the ice condition or ice numeral on which the speed of the vessel depends. An ice numeral is sampled from the distribution of ice numeral relevant to the place and time of the node. Speed is then calculated from the sampled ice numeral.

The ice breaker and a beset condition were modeled as a resource so that the utilization statistics could be collected. The start was kept on the first of January at Yokohama, and the vessel was made to transit eastward and then westward, continuing until 31 Dec, and the "round trips per year" were calculated. The other performance measures were time in ice, time in open water, port stay, canal-water time, repair days, and total distance. These were calculated to work out the cost elements for the economic model.

The main task in modeling transit is to represent the progress of time and space as the ship sailed through the passage complicated by the transient ice conditions which change with time and place. Changes with respect to time were modeled on a weekly basis, and the passage was geographically divided into nine legs. A week-and-a-leg combination was assumed to have a unique ice condition and therefore a unique speed, dependant on that ice condition. Transit through one of these combinations was considered as an "activity", whose duration was dependent on the length of the leg and speed achieved in that leg during that particular week. However, modeling each of these combinations separately would have resulted in 450 ($50 * 9 = 450$) activities, making the model cumbersome. Hence, the VSLAM ARRAY statement was used to represent all these activities with a single activity. The attributes of this activity were changed every time an entity commenced the activity. The attribute (duration) was defined with the help of an ARRAY variable, which have two subscripts, one representing the time and the other the legs. These subscripts were changed as simulation progressed to obtain a dynamic portrayal of the ship's advance. The subscripts define a $50 * 9$ matrix whose elements represents the unique distributions for the week $*$ leg combination. This distribution thus sampled was used to calculate the activity attribute or the speed. The distances for the legs were varied by another ARRAY with the row number fixed. From the distance and speed the duration is worked out.

Once the entity had completed 8400 h (50 weeks $*$ 168), it was routed out of the network and the statistics collected. The time check was made at activity completions only. As a result, the time in the system could have exceeded 8400 h. The remaining time to complete the year (or 8760 h – $365 * 24$) was considered to be the maintenance time. Convergence was checked and 300 runs were assumed to be sufficient.

For the Panama Canal transit the variation in speed was assumed to be triangularly distributed and the port stays and the canal transit times uniformly distributed. A spatial grid of 250 Nautical Miles (NM) was chosen. It was assumed that the sea conditions and hence the speed were likely to remain constant for this interval. The model also incorporated a time check at the end of this 250 NM interval, and the entity was routed out of the system if the simulation time exceeded 8640($360 * 24$), thereby making it possible to improve the accuracy of the round trip estimate. Thus, the Pacific leg with a distance of 7682 NM (Nautical Mile = 1852 m) was modeled by routing the entity 30 times through a 250 NM leg and completing the remaining distance in a single 182 NM leg instead of a single leg of 7682 NM.

The economic analysis was carried out on an excel spread sheet with @RISK add-in. The student version of @Risk was used. Distributions were worked out for cost data and entered in the cells. Prior to simulation the correlation among various inputs were specified, so that the model will not sample uncorrelated values for related variables. For example the steel prices and construction cost were positively correlated.

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