SHIPPING ROUTE OPTIMIZATION IN ICE

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ABSTRACT

Technological advances and changing climatic conditions provide commercial opportunities and some unique challenges for the Arctic region this century. Emerging trans-Arctic shipping routes in the Northwest Passage are a direct consequence of progressively receding sea ice in the Canadian Arctic archipelagic waters. This study conceptualized and developed a Computer-aided Arctic Route Optimization Model (CAROM) in the framework of a Geographical Information System (GIS) for ship voyage planning and tactical ice navigation. The model optimizes shipping routes in ice based on the charted depth of water, appropriate structural strengthening (Ice Class notation), and predicted and observed sea-ice conditions, with the latest available navigational and ice data in digital format. An incorporated ship transit-model provides speed-in-ice input to the route model essential to estimating the transit time critical for vessel scheduling and fuel cost estimation. The CAROM is operational, tactical in nature, and intended to act as a decision-making tool for the ice navigator. The presence of diminishing sea ice is an existential threat to surface navigation in the ecologically sensitive Arctic region, and ship-sourced oil pollution is a threat to Arctic marine ecology. Access to reliable satellite communication in the Arctic, the adoption of the Polar Code and the proposed e-Navigation framework of the IMO has opened new doors to implement and operationalize tactical navigation tools that may help in decision-making and risk mitigation in ice navigation. A seamless integration of the route optimization tool in the e-Navigation architecture is the desired objective that evolving technology may be able to achieve in future for the Mariners onboard. This research underscores the current limitations on the spatial resolution of ice data, electronic navigation chart coverage, and hydrographic surveys in the Canadian Arctic, to mention but a few. The transit time in ice predicted by the CAROM provides a comparative cost-benefit evaluation between a trans-Arctic route and the Panama Canal route for container ships of two different sizes trading between Rotterdam and Tokyo. The last few years have witnessed the arrival of mega container ships (Neo-Panamax type) primarily driven by economy of scale considerations, global trade dynamics, and expansion of the Panama Canal locks to accommodate such ships. The Cost Benefit Analysis reveals some interesting aspects of the container shipping business via the Northwest Passage and the difference a large container vessel of the Neo-Panamax type may result in assessing the overall cost comparison.

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DEDICATION

To my parents

Savitri and Sheo Shankar Pandey

For giving me their best

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List of Acronyms and Abbreviations

ACRONYM	EXPLANATION
AARI	Arctic and Antarctic Research Institute (Russian Federation)
ACIA	Arctic Climate Impact Assessment (2004)
AMAP	Arctic Monitoring and Assessment Program (Arctic Council Working Group)
AMSA	Arctic Marine Shipping Assessment (Arctic Council working group)
AIRSS	Arctic Ice Regime Shipping System
AIS	Automatic Identification System
ATAM	Arctic Transport Accessibility Model
AVPG	Arctic Voyage Planning Guide (Canadian Hydrographic Service)
AWPPA	Arctic Waters Pollution Prevention Act, 1970
BSB	File format used for Raster Navigation Charts
BSBv4	Raster Navigation Chart file format used by Canadian Hydrographic Service
CAROM	Computer-aided Arctic Route Optimization Model
CASPPR	Canadian Arctic Shipping Prevention Pollution Regulations
CHS	Canadian Hydrographic Service
CIS	Canadian Ice Service
CESM	Community Earth system model
CCSM4	Community Climate System Model

CBA	Cost Benefit Analysis
DGPS	Differential Global Positioning System
DMI	Danish Meteorological Institute
DNC	Digital Nautical Charts
DNV	Det Norske Veritas
ECA	Emission Control Area
ECDIS	Electronic Chart Display and Information System
ENC	Electronic Navigation Chart
ESRI	Environmental Systems Research Institute
FTP	File Transfer Protocol
GBS	Goal Based Standards (IMO)
GCMs	Global Climate Models
GDSIDB	Global Digital Sea Ice Data Bank
GHG	Green House Gases
GIS	Geographic Information System
IACS	International Association of Classification Societies
IHO	International Hydrographic Organization
IICWG	International Ice Charting Working Group
IM	Ice Multiplier
IMO	International Maritime Organization
IN	Ice Numeral
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IPCC	Inter-Governmental Panel on Climate Change
IRSS	Ice Regime Shipping System
ISM	International Safety Management Code (IMO)
ISS	Ice Service Specialist

JCOMM	Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology
MANICE	Ice Observing and Reporting Manual (CIS)
MARPOL	International Convention for the Prevention of Pollution from Ships
MCDA	Multi-criteria Decision Analysis
NA	Network Analyst Extension (ArcGIS)
NCAR	National Centre for Atmospheric Research
NEO-PANAMAX	Container ship (10000 TEUs) passes expanded Panama Canal locks
NIC	US National Ice Centre
NM	Nautical Mile
NORDREG	Vessel Traffic Reporting Arctic Canada Traffic Zone
NSIDC	National Snow and Ice Data Centre
NSR	Northern Sea Route
NSRA	Northern Sea Route Administration
NWP	Northwest Passage
OW	Non-ice strengthened ships
PANAMAX	Container ship (5000 TEUs) passes Panama Canal locks
PC	Panama Canal
PC-3	Polar Class-3 Ship
PC-4	Polar Class-4 ship
PC-6	Polar Class-6 ship
POLARIS	Polar Operational Limit Assessment Risk Indexing System
PWOM	Polar Water Operational Manual
RCP	Representative Concentration Pathways
RCP (4.5)	Medium-low radiative forcing

RCP (6)	Medium radiative forcing
RCP (8.5)	High radiative forcing
RIO	Risk Index Outcome
RV	Risk Value (POLARIS)
SAR	Synthetic Aperture Radar Telemetry
SDSS	Spatial Decision Support System
SIGRID	Sea Ice Grid (digital archive format)
SIGRID-2	Sea Ice Grid-2 (Ice chart Raster archive format)
SIGRID-3	Sea Ice Grid-3 (Ice chart Vector archive format)
SNZ	Safe Navigation Zone
SOLAS	Safety of Life at Sea (IMO convention)
SRV	Summer Risk Values (POLARIS)
STCW	International Convention on Standards of Training, Certification and Watch keeping for Seafarers
TC	Transport Canada
TPR	Trans-Polar Route
VDR	Voyage Data Recorder
VTS	Vessel Traffic (management) System
WGS-84	World Geodetic system, 1984
WMO	World Meteorological Organization
WRV	Winter Risk Values (POLARIS)
WWRNS	Worldwide Radio Navigation System (IMO)

Chapter 1: Introduction

1.1 Rationale for Research

The Arctic region braces itself for increased commercial activities this century as the progressive reduction in sea ice extent and thickness continues opening shipping lanes. A significant increase in maritime traffic evidenced in some parts of the Arctic, particularly the Northern Sea Route (Russian Arctic); projected to spread to the Canadian Arctic by the middle of this century (Smith and Stephenson, 2013). An interesting trend is also observed with increased trans-Arctic shipping traffic that uses the Arctic Ocean shipping lanes as a transit route between the Atlantic and Pacific Ocean (NSR-IO, 2016). Trans-Arctic or transit shipping via the Canadian Arctic is the focus of this study because the trans-Arctic routes are shorter (37%-40%) than the existing Panama Canal transits and may result in a faster turnaround of goods between the production economies of Asia and the consuming centers of North America and Europe. This study investigates shipping routes in the Canadian Arctic by proposing a route optimization model that is utilized to evaluate the said routes from a navigational and economic viability perspective.

The sea ice retreat evidenced in all parts of the Arctic and the likely consequences of emerging trans-Arctic shipping routes demands an in-depth study to establish if the Northwest Passage (NWP) is indeed an economically viable alternative to attract commercial shipping traffic from the popular southerly routes such as the Panama Canal. Under what conditions, it may be viable considering the limited summer navigation season even for ice class vessels; considering the costs involved and lack of credible infrastructure in the region. Maritime transport is a service industry, works on derived demand (Stopford, 1997) in a globalized and competitive world but is also risk averse and rooted in tradition. The risk that ice-infested waters pose to shipping traffic will exist even though sea-ice is thinning and receding in the Arctic (Pachauri & Meyer, 2015) as evidence suggests that ship damages occur in low to moderate concentrations of ice due to excessive ship speed and poor or inadequate judgement ((Enfotec Technical Services Inc., 1996) in relatively open waters. A collision with a single floe berg can lead to substantive pollution in the ecologically fragile Arctic region. Shipping companies may prefer to use the NWP route with ice navigation made safer through computer-aided voyage planning resulting in reduced risk, better scheduling and economic viability compared to the sub-Arctic route via Panama Canal. Ship-shore satellite connectivity ensures information transmission and sharing with the end user (the ship) almost instantly. There is an abject need for such solutions as shipping in the Northwest Passage increases and the perceived risk mitigated despite challenges in high latitude navigation and shortcomings in charting, hydrographical surveying among many others (Govt. of Canada-A, 2016). An optimized maritime routeing solution in ice may help in assessing the economic viability of the entire trans-Arctic route connecting ports in NE Asia and NW Europe; this study has set out to investigate. Commercial developments in the Arctic will require ships to move cargo and a pro-active risk mitigation tool as the one being discussed will enhance safety of shipping and reduce chances of pollution in the pristine region.

1.2 Research Objective

The Arctic leg (NWP) of a future trans-Arctic shipping route requires an optimized maritime routeing solution that may provide the much desired ‘least cost’ path for commercial ships to navigate the area with due dispatch. An optimized route for the purpose of this research is the most temporally expedient maritime route selected from a set of alternative routes in the NWP. It seeks the path of least resistance with sea-ice as impedance for ships appropriately classed and having a safe under keel clearance. Minimal ice interaction ensures better speed and lesser contact damage thereby reducing maintenance costs for ships in the long term and thus reduces cost of operation. Optimized routes also ensure better ship scheduling in sea-ice and enable ships to plan and execute the entire trans-Arctic voyage with greater certainty. Meaningful voyage planning in ice-infested waters can occur with a digital route optimization tool devised to predict the waypoints (geographical coordinates) a vessel must take with minimal sea-ice interaction during the passage. A simultaneous speed determination mechanism through the ice regimes will give a time of transit that the shipping companies require for ship scheduling and route planning between ports.

Ice avoidance serves a multitude of purposes including reduced ship maintenance costs, better speed, and overall safety of navigation that may reduce insurance premium and ship capital costs. This study embarked upon the proposed maritime route model using an appropriate GIS computer system focussing on a path of least resistance through sea-ice. GIS has served as a highly useful tool in providing solutions to road and rail transport networking problems in the last few decades and this study proposes to apply those concepts in the maritime domain. The route optimization model so conceived should give a good estimate of the transit time in the ice-bound segment that constitutes a critical element in predicting the economic viability of the entire trans-Arctic passage between Tokyo and Rotterdam for containerized shipping when compared with the Panama Canal transit between the two ports. The 'Required Freight Rate' per TEU[1] should be able to provide a sound basis for decision-making to a ship operator whether to take the Arctic route and under what conditions should it be economically viable with an appropriate ice class vessel and an assumed four-month summer navigation season. A solution to the problem of route optimization in ice seems to envelop different disciplines of study. It is imperative to scour the available literature and find out similar studies that may have been conducted in past as proposed in the research overview (section 1.5).

The objective is to investigate the economic viability of trans-Arctic shipping routes via the NWP by developing a GIS-based route optimization methodology and computer system that:

a) Enables voyage planning and operational readiness in the NWP before the ship enters the ice edge.
b) Improves transit economics in ice by predicting the "least cost"[2] route based on safety and economic constraints, strategically useful to the ship.

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[1] TEU: Twenty foot equivalent units
[2] Least Cost Route: Safest maritime route of least resistance chosen to ensure minimum ice interaction.

c) Allows re-routing based on changing ice conditions during the transit through NWP and acts as an operational decision-making tool.
d) Contribute to the economic analysis of transit shipping routes in the Arctic.

1.3 Research Questions

The following research questions are proposed in this study to achieve the stated objectives:

1. The Geographic Information System (GIS) most suitable to provide a workable maritime route analysis model.
2. Is the currently available ice and navigational data sufficient to devise a workable model in the identified GIS suite?
3. Is it possible to predict the ship speed in ice with an appropriate Ship Transit-in–ice Model for the NWP?
4. Can the proposed Route Optimization Model provide the "least cost" routing for a ship transiting the NWP?
5. Can this model be practically useful onboard? If so, how can a mariner benefit from the same?
6. How does the comparative economic analysis help a liner shipping[3] company in vessel deployment through the Northwest Passage?

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[3] Liner Shipping: Containerized shipping

1.4 Research Methodology

The proposed research methodology is first to review the current state of the art in GI[4] systems and the data availability in the public domain from relevant sources to support the development of a routeing model for the Northwest Passage. The next step is to develop a GIS-based Arctic Shipping Routeing Model, using currently available tools, data, and information for specific routes identified and plotted on paper charts and ENCs of the NWP. The model will consider both transit safety and speed optimization based on hydrography and ice conditions. This model will then be tested for technical viability based on comparison with independent (non-assisted) ship transits to determine if the predictions of the routeing model are consistent with actual ship voyage. The final step is to implement the optimized route in sea-ice to develop a more detailed economic analysis of trans-Arctic ship transits in comparison with popular Pacific-Atlantic shipping routes through the Panama Canal. A successful outcome of this research will demonstrate that a successful Route Optimization Model may provide an operational method of digital voyage planning in sea-ice. The accuracy of transit time predicted by the Model, will offer more realistic economic comparisons with the sub- Arctic routes such as the Panama Canal for ships engaged on inter-continental trade routes.

1.5 Research Overview

This section outlines (Figure 1) a complete overview of the intended research project. The study proposes three separate models to achieve the stated objectives namely:

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[4] GI: Geographic Information

1. Computer-aided Route Optimization Model to predict routes in the NWP
2. Ship Transit-in-ice Model: Predict the average speed in ice.
3. Economic Route Model: Cost-Benefit Analysis- Comparative study of the trans-Arctic route between Tokyo and Rotterdam with the Panama Canal route for containerized shipping.

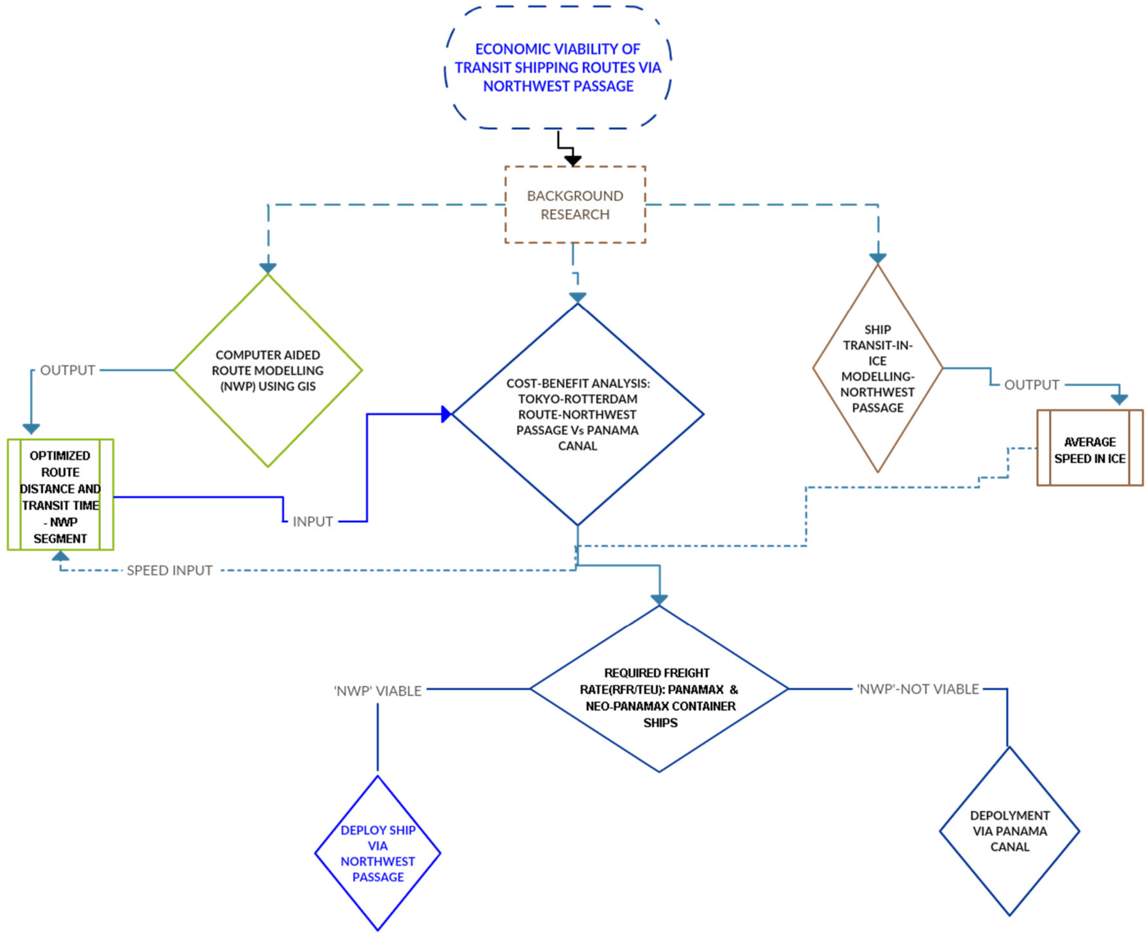

Figure 1: *Schematic Overview: Proposed Research*

Source: Author

The flowchart as presented encapsulates a snapshot of the proposed research.

1.6 Dissertation Outline

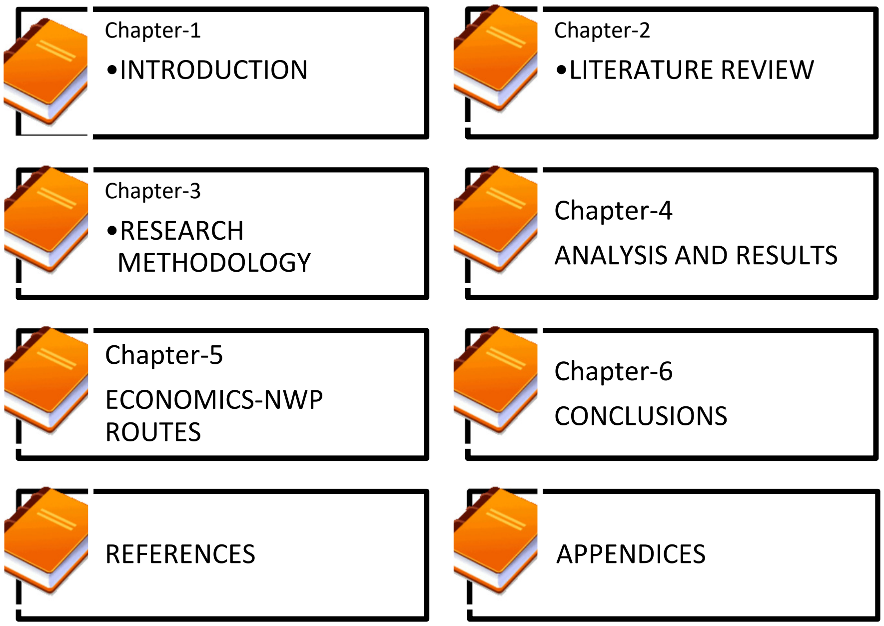

Figure 2: *Illustration-Dissertation Outline*

Source: Author

The following chapters describe the dissertation in brief:

Chapter1: An introductory chapter that puts into perspective the rationale for the proposed research, its objectives, and the research questions formulated. The research overview presents a clear strategy on the way forward to achieve the research objectives.

An outline of the research methodology is presented to achieve the following:

a. Conduct voyage planning in ice and predict the transit time in ice.
b. Conduct a comparative economic analysis of a trans-Arctic route (via NWP) between two named ports (Tokyo and Rotterdam) with adequately designed (PC-4) hypothetical container ships (two different sizes) and their non-ice class counterparts via the Panama Canal.

Chapter 2: A comprehensive literature review of the three components to the research envisaged to understand the following:

a. The appropriate GIS methodology adopted for a Computer-aided Maritime Route Model for the Northwest Passage.
b. A Ship Transit in-ice Model required incorporating ice data and requisite ship parameters.
c. Cost Benefit Analysis (CBA) for trans-Arctic container shipping when compared to shipping through the Panama Canal for two ship classes (PC-4, OW) and two different ship sizes.

The chapter also delves into decision making aspect of GIS by considering literature on Multi-criteria Decision Analysis and rule based expert knowledge employed in creating a ‘Safe Navigation Zone’.

Chapter 3: The methodology adopted to construct and execute the proposed models is based on the previous chapter and includes the existing data resource available publicly to implement working models that may be useful in decision making for ships, shipping companies, and other stakeholders. Assumptions made in arriving at the ‘Safe Navigation Zone’ (SNZ) through Multi-criteria Decision Analysis (MCDA) are to be included in this chapter.

Chapter 4: This chapter contains a comprehensive discussion and analysis of the results based on the optimized route model and Ship Transit-in-ice model outputs. The Route Optimization Model is subjected to validation and verification process with the help of two case studies for June and September transit months; a simulation study conducted to test all the three transit routes under various conditions of ice impedance. A validation of the NWP route model by reconstructing and comparing the actual route taken by MV ‘Nunavik’ in September 2014 is also carried out. This chapter will give us the results of the validation and verification process, prove if the models as conceptualized are indeed workable, and justify the research questions as proposed.

Chapter 5: This chapter will discuss the results of the Cost-Benefit comparison of a trans-Arctic shipping route and Panama Canal route between the two ports as proposed. The Economic Cost Model depends on the outputs from the Route Optimization model for an accurate cost comparison of the two shipping routes. The Economic Cost Model assesses the economic viability of the NWP route that may be useful to a shipping company whether it prefers the Arctic route over the normal Panama Canal route during the Arctic summer navigation season.

Chapter 6: The chapter summarizes the entire study and reflect upon the success or failure of the proposed concepts. It is pertinent to discuss the limitations and challenges encountered in the development and execution of the three models that may result in further research leading to better modelling in the future. Computer-aided voyage planning can only have a bright future going forward as this chapter delves in future research applications of this project in the light of IMO’s ongoing e-Navigation Strategic Implementation Plan.

Chapter 2 Literature Review

2.1 Introduction

This research encapsulates an interdisciplinary investigation that integrates topics from nautical science to maritime economics with ice engineering and GIS to provide the requisite support. The literature review thus covers a range of subjects but seeks state of the art in each area on the practical level to address the overall research questions.

2.2 Geographic Information Systems

A Geographic Information System is an organized collection of computer hardware, software, people, data, and procedures (Burrough et al., 1998). Over the past four decades, considerable progress has been made in developing tools that are designed to capture efficiently, store, query, analyze, and display all forms of geographically referenced data (Goodchild, 2009). The arrival of the internet in the 1990's has made it possible to share spatial data with multiple users in remote locations including transport vehicles on road and rail. Existing technologies for capturing such information include Global Positioning Systems (GPS) to determine positions on land, air, and sea; image acquisition through remote sensing techniques including satellites, aircraft and drones and the GIS architecture to assimilate all the above spatial data for analysis purposes. What sets GIS apart from other database management systems (DBMS) are the geo-visualization capability and the inherent functional complexity of such regimes. The analytical capacities of the GIS make it much more than an automated cartographic application system while the DBMS features are incorporated to manage the spatial and topological relationships between georeferenced entities (Goodchild, 2009).Visualization or mapping is only a small part of what makes GI systems different, it includes the analysis of geographically referenced data, the ability to integrate geo-spatial data from many different sources including dynamic spatial modelling that could be very useful in devising future maritime Network Models.

Although, the transportation world was late in embracing GIS (Thill, 2000); transportation research has become increasingly interdisciplinary in the last thirty years reflecting the multi-faceted dimension of transportation infrastructure and cargo flows. GIS is computer –based and integrates multiple functionalities in one rather seamless environment that leads to efficiency benefits for the end user, a convincing case for organizations to adopt GI systems. Three kinds of GIS models are relevant in the transportation context (Goodchild, 1998) namely, Field Models, Discrete Models, and Network Models. The last named is pertinent to this area of study. Network Models represent topologically connected linear entities such as road and rail networks built around the concept of arcs and nodes on a continuous georeferenced surface. This study defines a topology for a maritime network and applies the GIS-Network Model concepts to conduct route optimization in the NWP. GIS software like many other software products comes in two different packages- Commercial Software and Open Source platforms. The popular commercial offerings that the study reviewed include ESRI's[5] ArcGIS, GEOMEDIA and MAPINFO besides the Open Source software packages namely: MAP WINDOW, QGIS, qVSIG and OPEN JUMP (Selamat et al., 2012). Almost

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[5] ESRI: Environmental Systems Research Institute, Redlands, California

all the systems provide a desktop application as well as an online environment for cartography and spatial analysis. The proposed maritime route network analysis in GIS will use an electronic map layer (base layer) of the area under reference and information about sea ice of the area in a digital format compatible with an appropriate software suite.

2.2.1 Digital Ice Charts-Arctic

The Global Digital Sea Ice Data Bank (GDSIDB) provides digital ice charts of the Arctic and Antarctic in an archive format compatible with WMO standards (IICWG, 2013). The international ice centres most actively involved in providing information to the global ice data bank are the AARI, CIS, DMI, and NIC through the International Ice Chart Working Group (IICWG). The ice centres developed a vector format for archiving digital ice charts (SIGRID[6]) in 1981 as adopted by the WMO in 1989. The SIGRID-2 format adopted by the WMO in 1994 is a Raster data format that stores ice information on grids. The vector format (SIGRID-3[7]) as passed in 2004, preserves all information in the original chart; charts can be re-projected without loss of information and easily converted to the Raster format if necessary. The ice centres prefer the SIGRID-3 format because many of the current production systems employ commercial GIS software. There are standard tools in many other GIS software platforms that can convert or directly use 'Shapefiles'. For example, QGIS can use 'Shapefiles' and so can open source GIS software such as IDRISI and MAPINFO. 'Shapefiles' produced without commercial GIS software will require the

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[6] SIGRID: Sea Ice Grid format developed (1980) to incorporate paper charts to digital format.

[7] SIGRID-3: A vector archive format for sea ice charts as adopted by CIS.

development of custom software (JCOMM, 2004) hence commercial GIS software is a convenient choice.

2.2.2 Digital Nautical Charts: Canadian Arctic Waters

Electronic maps of the Arctic waters are available in the form of Digital Nautical Charts (DNC) published by various national hydrography organizations. The Canadian Hydrographic Service (CHS) publishes nautical paper charts as well as digital nautical charts of the Canadian Arctic, relevant to this study. The CHS publishes digital nautical charts in two formats: Vector format (ENC) and Raster format (RNC). The ENCs are GIS compatible (Fisheries and Oceans Canada-A, 2016) and can be used as a base layer for spatial analysis.

2.3 Projections: Decrease in Arctic Sea Ice

The projected decrease in Arctic sea ice extent and the likelihood of a rise in maritime traffic leading to a shorter transit route through the Arctic Ocean provided the initial impetus for this research. Hence, it is pertinent to examine the literature that provides credence to the above assertion. The IPCC[8] contends that the annual mean Arctic sea-ice extent decreased over the period 1979 to 2012, with a rate in the range 3.5 % to 4.1% per decade (Pachauri & Meyer, 2015). The IPCC report also concluded that Arctic sea-ice extent has decreased in every season and in every successive decade since 1979 (Maslanik et al., 2007; Comiso, Parkinson, Gersten and Stock, 2008; Kwok et al., 2009; Stroeve et al., 2012) with the most rapid decrease in decadal mean extent in summer (*high*

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[8] IPCC: Intergovernmental Panel on Climate Change

confidence)[9]. Anthropogenic influences is understood to be the likely cause of Arctic sea-ice diminishing since 1979 and may also have contributed to an increase in the global mean sea level rise and the global upper ocean heat content observed since the 1970s (Kay, Holland and Jahn, 2011; Day, Hargreaves, Annan and Abe-Ouchi, 2012). Smith and Stephenson (2013) demonstrated increased access to vessels including non-ice class ships (OW) for all Representative Concentration Pathway (RCP) scenarios (Appendix 1) this century including the NWP. The RCP's are four greenhouse gas concentration trajectories adopted by the IPCC in its Fifth Assessment Report (Pachauri & Meyer, 2015) used for climate modelling and research. The IPCC describes four possible climate futures for the earth depending on how much greenhouse gases are emitted in years to come this century. The four RCPs, RCP2.6, RCP4.5, RCP6, RCP8.5 (Appendix 1) essentially describe mitigation scenarios related to climate change. RCP2.6 represents the most stringent mitigation scenario followed by two intermediate scenarios (RCP4.5, RCP6) and one scenario with a high GHG emission in RCP8.5. The last named equates to the maximum projected loss of sea-ice in the Arctic and predicts a longer navigation season for ships of all types in the NWP as discussed in Chapter 5.2.1.

GCM simulation studies provide enough scientific evidence on the spatial extent of sea-ice receding across the Arctic region, though some studies may differ on the pace of temporal changes (Wang and Overland 2012; Vavrus, Holland, Jahn, Bailey and Blazey, 2012) in various parts of the Arctic this century. In fact, one of the main consequences of climate change for maritime commerce in the Arctic region is contained in a key finding

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[9] High confidence:8 out of 10 chance

of the Arctic Climate Impact Assessment which states- “*Reduced sea ice is very likely to increase maritime transport and access to resources in the Arctic*” (ACIA, 2004, #6, pp.11).

2.4 Sea Ice Data Collection and Ice Charts

Remote sensing is one of the best methods of capturing the sea ice extent and thickness currently available (Johannessen, Alexandrov and Frolov, 2007) from space and air using satellites and reconnaissance aircraft respectively. The presence of sea-ice is the largest single differentiator for ship navigation in the Arctic Ocean compared to any other ocean and hence the most important hydrometeorological factor which, needs to be determined with precision. Besides imposing a physical barrier, the ice also keeps moving and undergoes deformation (shape and size) due to changes in other environmental variables such as ambient temperature, wind direction, and magnitude, ocean current direction and rate (Appendix 2) among others. Forecasting sea-ice is thus a complex mathematical modelling task at the best of times. The sea-ice data set is a critical, if not the most important component of the proposed route optimization process. The US National Ice Centre (NIC) in close cooperation with the NSIDC[10] has been producing Ice Climatology charts for the Arctic since 1972 (NSIDC-A, 2016). Ice chart production and presentation has greatly improved since 1972; the NIC started producing Regional Ice Analysis Charts with Synthetic Aperture Radar (SAR) imagery by 1996 (Bertoia, Falkingham and Fetterer, 1998) that made detailed analysis possible. The NIC introduced the use of

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[10] NSIDC: National Snow and Ice Data Center, Boulder, Colorado

ESRI's ArcGIS software in 1996 as the production shifted to the digital environment in the late 1990's (Fetterer and Fowler, 2006).

The accuracy and image resolution provided by remote sensing is widely dependent on the satellite data capture technology in use and may be sensitive to weather or light (optical and infrared range). SAR telemetry, however, uses the microwave range of data capture and improves the data quality significantly, unaffected by weather or light interference (NSIDC-A, 2016). Microwave radiation is of two types: Active and Passive microwave. Active microwave implies radiation emitted from the surface of the object when interrogated by satellite transponders such as SAR. Microwave radiation naturally emitted by the Earth is termed Passive radiation, and the sensors can detect sea ice through clouds in day and night over a large area due to low radiation properties. These sensors have been used aboard NASA satellites for Arctic sea ice mapping since 1972 and form the bulk of the historical sea ice data mapping available today. Improved technology equipment is used in mapping ranging from ESMR [11](1972) to AMSR-E[12] launched in the year 2002 aboard the Aqua satellite (NSIDC-B, 2016). The low energy levels emitted in the process, however, is a drawback of this method. Active Radiation Sensors of the SAR type have excellent resolution and can detect even small leads in ice. The Canadian Ice Service uses SAR imagery through the RADARSAT mission of the Canadian Space Agency (NSIDC-C, 2016). The bounce back technology in Radar systems is a very useful tool in detecting thick ice from thin ice and ice concentration data on charts is, therefore, more accurate with Active Radiation Sensors.

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[11] EMSR: Electrically Scanning Microwave Radiometer (used in 1972)

[12] AMSR-E: Advanced Microwave Scanning Radiometer-Earth Observing System

The Canadian Ice Service (CIS) produces ice charts for the Canadian waters; the datasets cover the Northern (Eastern and Western Arctic, Hudson Bay) and Southern Canadian Waters (Great Lakes and East Coast). This study used datasets (select charts) for the year 2014, although any of the datasets from the year 2006 onwards may be employed. The information depicted on the ice charts follows the World Meteorological Organization (WMO) terminology (NSIDC-D, 2016). The regional sea ice data is available in the SIGRID-3 format and fully compatible with ESRI's ArcGIS. The dataset comprises of several files including an attribute file that describes the total ice concentration, partial concentration, stage of development (ice thickness) and ice form that are essential for mapping the ice regime. Each ice chart contains up to 72 hours of input data as noted in each attribute data file (NSIDC-D, 2016). CIS contends that the "*reliability and accuracy of the data set is directly related to the availability, resolution, and effects of atmospheric (cloud, daylight, etc.) and ground (snow, rain, sea state, etc.) conditions on the source of information*" (NSIDC-D, 2016). CIS has implemented a schema for the SIGRID-3 Vector archive format and has allocated codes to interpret the attribute data tables that correspond with the MANICE[13] description and the WMO Egg Code[14] (Appendix 3). Environment Canada publishes the SIGRID-3 schema for sea-ice thickness (Appendix 4), total ice concentration (Appendix 5) and floe size (Appendix 6) that is used in calculation of Ice Numerals and sea-ice thickness in this paper (Environment Canada). Temporal coverage of the ice charts is available from the year 2006 onwards as part of the CIS SIGRID-3 dataset and issued once a week in the summer and bi-weekly in the winter for

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[13] MANICE: CIS-Manual of Standard Procedures for Observing and Reporting Ice Conditions

[14] Egg Code: Depiction of ice data in an ice chart

northern Canadian waters. The CIS ice charts constitute the cornerstone of the Route Optimization Model since the ice polygons[15]contribute in calculating the speed for the ship transit-in-ice model besides the Ice Numeral/RIO determination.

2.4.1 Limitations- Ice Data Charts

Ice concentration data collected from passive microwave radiation techniques may not be as reliable as SAR (active microwave) telemetry data. Passive microwave radiation data is known to underestimate sea ice concentration (Fetterer and Untersteiner, 1998; Comiso and Kwok, 1996) and NIC charts preceding the mid-1990s do have passive microwave data content. The melt ponding[16] on the sea surface during the summer season is the likely reason. Canadian Ice Service charts do not, however, rely on Passive microwave data alone and tend to show substantial differences when compared with Active microwave data (Agnew and Howell, 2003). NIC analysts avoid using Passive microwave methods if ice concentration data from other sources is available (Fequet, Ballagh, Chagnon and Fetterer, 2009). The SIGRID ice charts contain vector data (points, lines, and polygons) with no native resolution (Fequet et al., 2009) when compared to gridded data that leads to a loss of information when converting chart information to a grid with fixed points. SIGRID-3 Vector archive format adopted by CIS since the year 2006 is devoid of this deficiency. The climatology products from NIC are presently available in the standard EASE- Grid[17] data binary (.bin) format and ArcGIS database (.mdb) files. The US National Ice Centre intends to issue climatology products for various other GIS

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[15] Ice Polygons: Shape form depictions on Vector Charts

[16] Melt ponding: Pools of open water that form on sea ice in summer/spring season

[17] EASE-Grid Data: Equal Area Scalable (25km) Earth Grid (.bin) files

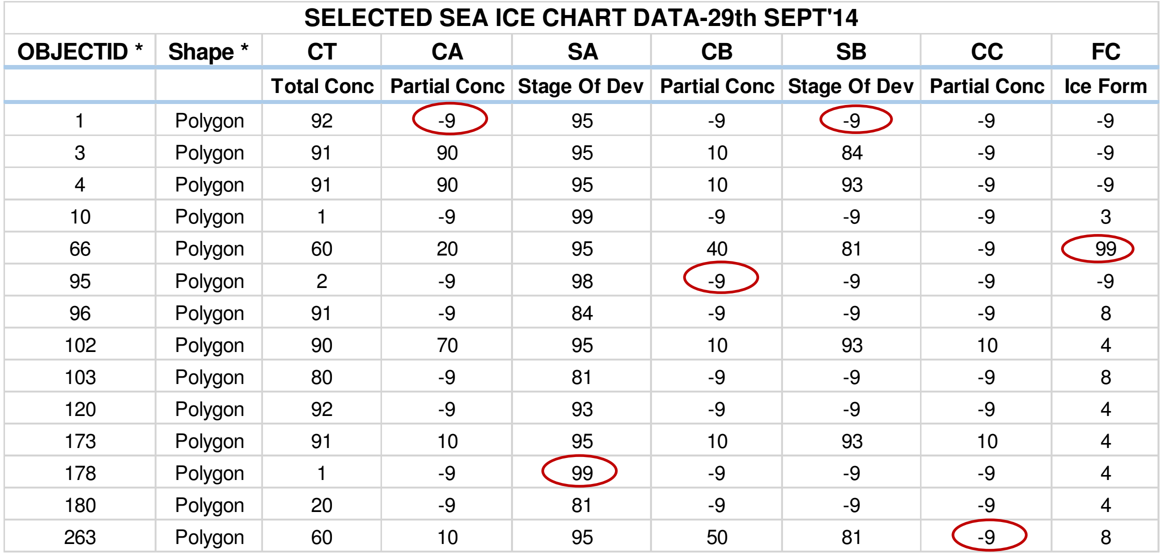
software in the future. The majority of the inconsistencies in ice chart data production and conversion date back to the archived data files (1972-1994) and the Canadian Ice Service publishes the errors observed in their ice datasets for users to exercise caution. It is pertinent to note that the ice charts may have inherit errors like any other map product related to classification and location accuracy based on scale factors and how the data was vectored if the source of information was a raster satellite image (e.g. sea-ice information). If the resolution of the image data was 100m the locational accuracy of the boundary for different ice class will be approximately ½ pixel width or 50 metres. It suffices to assume that no map is 100% accurate because of the processing used to create the information. CIS does not produce iceberg charts for waters north of 60°N (Environment and Climate Change Canada-A, 2016) but the ice charts do indicate the polygons (areas) where icebergs may be present. It is prudent to navigate with safe speed in such areas that may have minimal ice concentration but infested with bergy bits, floe bergs and icebergs. Reduced daylight hours, fog in the high latitudes particularly in the summer navigation season and prolonged periods of darkness make navigation challenging in open waters of the Arctic.

2.4.1.1 Limitations- Ice Chart Attribute Data

The ice chart attribute data from 29 September 2014 (Table 1) shows a representative sample of information related to total ice concentration (CT), partial ice concentration (CA, CB, CC), stage of development (SA, SB, SC) and the form of ice (FC) depicted in SIGRID-3 codes. Ice data inconsistency is observed in rows with Object ID 1 and 3 and various other places in the table. The CT numbers in both polygons show complete ice coverage (9/10 to 10/10 ice), but the partial concentration in the first row (-9) indicates a missing value (dummy variable) that makes it difficult to analyse the ice regime accurately.

Table 1

Ice Chart Data –Sept 29, 2014



SELECTED SEA ICE CHART DATA-29th SEPT'14

OBJECTID *	Shape *	CT	CA	SA	CB	SB	CC	FC
		Total Conc	Partial Conc	Stage Of Dev	Partial Conc	Stage Of Dev	Partial Conc	Ice Form
1	Polygon	92	-9	95	-9	-9	-9	-9
3	Polygon	91	90	95	10	84	-9	-9
4	Polygon	91	90	95	10	93	-9	-9
10	Polygon	1	-9	99	-9	-9	-9	3
66	Polygon	60	20	95	40	81	-9	99
95	Polygon	2	-9	98	-9	-9	-9	-9
96	Polygon	91	-9	84	-9	-9	-9	8
102	Polygon	90	70	95	10	93	10	4
103	Polygon	80	-9	81	-9	-9	-9	8
120	Polygon	92	-9	93	-9	-9	-9	4
173	Polygon	91	10	95	10	93	10	4
178	Polygon	1	-9	99	-9	-9	-9	4
180	Polygon	20	-9	81	-9	-9	-9	4
263	Polygon	60	10	95	50	81	-9	8

Note: Adapted from CIS ice chart dataset September 29, 2014, Retrieved March 23, 2016, from ftp://sidads.colorado.edu/pub/DATASETS/NOAA/G02171/Western_Arctic/

The Stage of Development (SA, SB, SC), Partial Concentration (CA, CB, CC), and Ice Form (FC) column codes exhibit data inconsistency as evident from the table. It is hard to estimate the average sea-ice thickness with a ‘dummy variable’ (-9) present in the mix that introduces an uncertainty in averaging ice thickness. Information on floe size that is critical to voyage planning becomes unreliable with missing values and ‘unknown parameters’ (99). An accurate estimation of ice concentration is also not precise with so many missing variables. This study has done an estimation of average ice thickness for each partial concentration (CA, CB, CC) category based upon the ice thickness (SA, SB, SC) data populated in adjacent polygons to arrive at an average value for the columns where the data depicts a missing variable (-9) or an unknown parameter (99). A visual assessment from the bridge of an icebreaker/ship by the Ice Service Specialist (ISS) or the ice Pilot/Shipmaster is the only other way to estimate those numbers with better accuracy. The average ice thickness values arrived due to the above estimation introduces an additional error or uncertainty to the Model parameters. This is an inherent limitation in the sea-ice attribute data tables used for calculating the composition of the ice regimes to conduct voyage planning. The resultant uncertainty introduced in sea-ice thickness averaging has not been accounted for in the Model.

2.4.2 Canadian Ice Service (CIS)

The Canadian Ice Service (CIS) provides fairly timely and accurate information of ice climatology in Canada's southern waters (south of 60°N) despite limitations in spatial resolution and data quality issues. Ships have direct access to ice and iceberg information via satellite link as well as through coastal weather stations via the facsimile receiver. Satellite communication technology enables ships to access the CIS website that contains a substantial amount of information on ice and iceberg conditions and access to the Canadian Ice Service archives. The daily ice charts represent the best estimate of ice conditions at the time of image acquisition (4 hours before transmission), based on an integration of data from a variety of sources, such as satellite observation, ship, and aircraft-based visual observations. The charts describe ice concentration in tenths, ice types or stage of development and the form of ice. The charts depict ice information in the Egg Code format and colour coded using the WMO[18] Standard. The Egg Code displays basic data concerning concentrations, stages of development (age) and forms (floe size) of ice contained in an oval. A maximum of three ice types are described within the oval; the coding associated with it conforms to international standards, and the entire ice chart may be interpreted from the codes and associated symbols and abbreviations contained therein.

Regional ice charts for the Eastern and Western Arctic are issued weekly, year-round from CIS (Environment and Climate Change Canada-A, 2016) and covers all the routes in the NWP (Appendix 7).The Ice Manual (Environment and Climate Change Canada-D, 2016) published by CIS contains the standard procedures for observing and reporting ice conditions in the Canadian Arctic. CIS uses SAR satellite imagery for ice data mapping and analysis. The standard width of the satellite data collection for ice information is about 500 kilometres with a resolution of 100 meters. The geometric accuracy of an ice edge[19] is within 630 meters with 100 meters' pixel resolution (Image Analysis Chart, 2016). This is a locational error in the ice charts since vector data is derived from satellite imagery and the locational accuracy of the vector ice polygons are no better than the source. This error has not been accounted for in the modelling process.

The Northern Canada, Vessel Traffic Services Zone Regulations, has established the Northern Canada Vessel Traffic Services (NORDREG) Zone (Appendix 8). It implements the requirements for vessels to report information before entering, while

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[18] WMO: World Meteorological Organization

[19] Ice edge: Demarcation boundary between open water and sea-ice

operating within and upon exiting Canada’s northern waters. The Regulations enhance the safety of ships, crew, and passengers, and are expected to safeguard the unique and fragile Arctic marine environment. These Regulations ensure that the most efficient services be made available to accommodate current and future levels of marine traffic in the Canadian Arctic. Vessels of 300 GT[20] or more are required to report to NORDREG, consisting of a sailing plan, position report, final report, and a deviation report, if applicable. Ship reports to NORDREG, originally implemented in 1977, as a voluntary scheme were made mandatory since July 1, 2010. Contravention of the mandatory reporting guidelines may result in heavy fines imposed under the Canada Shipping Act (Canada Shipping Act, 2001).

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[20] GT: Gross Tonnage: measurement of ship’s internal volume expressed in Tons

2.5 Maritime Charting: Digital Data and e-Navigation

How could one conduct route modelling in the maritime domain given the fact that there are few instance of research papers available in GIS literature? Moreover, this study is attempting to provide a solution that is operational and practically useful onboard a ship prior to and during ice navigation. For an ice navigator, the ideal approach to voyage planning would be the determination of waypoints (path of least resistance) well in advance of the intended passage to plan for contingencies such as an icebreaker escort or any other exigencies on the optimized route. A tactical voyage in sea-ice involving change of route and or speed during the passage with the latest ice charts will provide the ultimate decision making tool that a Shipmaster can hope for. An out of the box approach is necessary to provide solutions as ship transport embraces the digital data concept and transforms from hardcopy nautical products (books and charts) to electronic navigational products using 'Geodatabase' storage, data transfer protocols and geoprocessing tools. The Electronic Chart Display and Information System (ECDIS) uses electronic navigation charts for real-time navigation (SOLAS-Amendments 2010 and 2011) since the year 2002. The Electronic Navigation Chart (ENC), a digitized version (Vector format) of the nautical paper charts has essentially brought the maritime map from the chart-table to electronic display screens on the ship's bridge. The ECDIS[21] equipment not only displays the electronic navigation chart but also by its versatility and interfacing capability with shipboard navigation equipment has transformed the 'art' of navigation into a robust scientific decision-making tool for the mariner. Interfacing with onboard Radars, depth

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[21] ECDIS: Electronic Chart Display and Information System-shipboard equipment

sounding equipment, Gyro compass[22] and the DGPS[23] makes advanced navigation much more integrated with the ECDIS as the ice navigator can monitor the passage plan and collision avoidance on a single screen with radar images ‘on the fly.' Gyro stabilization capability adds more functionality to the ECDIS as the display could be oriented in a north-up or head-up configuration as preferred by the observer. The ECDIS forms an integral component of IMO’s global e-navigation Strategic Implementation Plan (SIP) and architecture (Appendix 9) as approved by the Maritime Safety Committee (MSC 94) in the year 2014. IMO defines e-navigation as *“the harmonized collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to ensure berth to berth navigation and related services for safety and security at sea and protection of the marine environment”* (IMO, 2016). The principal objective of the SIP is to provide e-navigation solutions in five key priority areas that encapsulate the following:

a. User-friendly bridge design
b. Integrity and reliability of bridge equipment
c. Presentation of information in graphical displays received via communication equipment
d. Standardized and automated reporting
e. Improved ‘Vessel Traffic Service’ communication portfolio

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[22] Gyro Compass: Primary compass used for shipboard direction finding

[23] DGPS: Differential Global Positioning System, a variant of GPS shipboard equipment

The above tasks are mandated (IMO-A, 2014) to be completed during the period 2015-2019. The SIP will provide the industry with harmonized information to implement better product design in the future. A strategic framework has been adopted at the IMO to achieve the deliverables within the targeted period (IMO-C, 2014). The US NOAA[24] publishes ENC data that is downloadable in a variety of GIS/CAD[25] formats using the IHO S-57 format. The data can be analysed in ESRI's ArcGIS (NOAA, 2016) that includes coastal topography, bathymetry, landmarks, and maritime boundaries familiar to the mariner. ArcGIS for Maritime Charting provides an entire suite of products well suited to maximize the value the Electronic Navigation Chart (ESRI, 2016) in the GIS domain. The same platform is utilized by the CIS to produce and analyse ice charts; ArcGIS also support the Canadian Hydrographic Service ENC dataset (.000[26]) file. (Fisheries and Oceans Canada-A, 2016).Electronic Navigation Charts provide the base layer for the spatial data query and analysis of the hydrography details and object information required in ArcMap. ENCs can be imported into the 'ArcMap'[27] by a standard protocol S-57 developed by IHO in a strictly non-navigation[28] environment. IMO and IHO[29] have set international standards for ENC production, ECDIS equipment as well as the electronic data transfer standard (S-57). IHO's S-57 protocol enables the import of ENC files into a GIS system such as ESRI's ArcGIS platform used in this study. CHS digital charts are available as Raster Navigational Chart (RNC) either in the

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[24] NOAA: National Oceanic and Atmospheric Administration (USA)

[25] CAD: Computer-Aided Design

[26] .000 file: chart installation data files

[27] ArcMap: An ArcGIS workspace used to edit and analyse data

[28] Non-navigation: Not to be used for on-board ship navigation

[29] IHO: International Hydrographic Organization

BSB format or as Electronic Navigational Chart (ENC) in the S-57 vector format. The RNC is a scanned, geo-referenced production of the paper chart, and the ENC contains vector spatial data of the nautical chart features. The RNC’s (BSBv4) produced by CHS are not compatible in GIS (Fisheries and Oceans Canada-A, 2016); hence the study has adopted the ENC for route modelling convenience.

2.5.1 Electronic Navigation Charts (ENCs)

The ENCs by their data content including object attributes and metadata are ‘smart charts’ that go beyond nautical paper charts or RNC’s. They not only depict the maps but a wealth of geospatial information that is easily stored, queried, analyzed and shared in a GIS environment. This gives a powerful platform to the digital format of nautical paper charts that is suitable for position fixing and route planning purposes. ‘ArcMap’ displays electronic navigation chart data presented in several layers (IHO object classes) and the operator can switch the layers ‘off’ and ‘on’ for querying and spatial analysis. One can imagine an updated nautical paper chart superimposed with the information from Sailing Directions, Tide Tables, List of Lights and other navigational publications combined. The CHS does not provide complete ENC coverage (Fisheries and Oceans Canada, 2013) in the Northwest Passage currently (Appendix 10), hence paper charts have been used to fill out the route network on a considerable stretch of the M’Clure Strait route, parts of the Prince of Wales Strait route and the Peel Sound route, the three routes identified in the NWP. Complete ENC coverage of the NWP is necessary as the region gears up for commercial shipping triggered by the progressive depletion of sea-ice.

2.5.2 IHO-S-57 Protocol

The S-57 protocol for data transfer set out by the IHO enables transfer of (.000) files that contains ENC data into ArcGIS, a non-navigational environment. The ArcMap itself should not be used for navigation at sea but the results (waypoints, speed etc.) are to be transferred to electronic navigation charts or hard copy paper charts for navigation purposes.

ArcGIS users thus have vector data sets of the Electronic Navigation Charts appropriately geo-referenced for data query and spatial analysis. It is worthwhile to underscore that all mapped vector data has some degree of error depending on map scale and source of information used for mapping. The ArcGIS environment is strictly non-navigational[30], meant for research and analysis purposes such as a desktop or a mobile digital device. The 'ESRI S-57 viewer'[31] allows users to view S-57 data in compliance with S-52 standards. IHO special publications S-52, S-57, and S-63 are technical standards developed for digital data exchange as specified in the IMO performance standards for ECDIS. IHO S-57 is the current IHO Transfer Standard for Digital Hydrographic Data. In addition to the main part there are two appendices to S-57: Appendix -A (IHO-'A', 2000) is the object catalogue and data schema set to describe real-world entities on ENCs while Appendix-B (IHO-'B', 2000) contains product specifications adopted by IHO. Currently S-57 edition 3.1 is in use and supported by ESRI but has several limitations notably in inflexible maintenance standards and cannot

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[30] Non-navigational: ArcMap is not being used for ship navigation-only meant for data analysis on PC/mobile devices.

[31] S-57 Viewer: An add-on that allows ArcGIS users to view S-57 data

support future requirements such as gridded bathymetry or time-varying information among others (IHO-'C', 2009). A major revision of the S-57 was conducted by an IHO committee in November 2000 resulting in the development and introduction of S-100 that includes a new exchange data format. The Universal Hydrographic Data Model, as it is now called was adopted by the IHO on 1 January 2010, thereby becoming an active international standard.

2.5.2.1 Universal Hydrographic Data Model (S-100)

S-100 standard is the new name for Edition 4.0 of the S-57 developed by IHO in 2005. It supports a wide variety of hydrographic digital data sources, includes new spatial models to support imagery and gridded data, 3-D and time varying data and new applications that go beyond the scope of traditional hydrography, most notably marine GIS. S-100 also includes new terminology that have been redefined or modified from the current Edition 3.1 of S-57. The S-100 comprises multiple components that are aligned with ISO 19100 series of geospatial standards that enables hydrographic data to be included in many more general geospatial applications than before. The S-100 Geospatial Information Registry supports several features not available with the S-57 standard that includes Feature Catalogues, Flexible version Control, Metadata, Spatial Geometry, Imagery and Gridded Data, Multiple Encoding and most notably Continuous Maintenance ((IHO-'C', 2009).

2.5.3 S-100 and e-Navigation

In early 2011, The IMO Correspondence Group on e-Navigation reported to the IMO that S-100 be considered as a baseline and an important element in the development of the on-going e-Navigation architecture. Work is already underway to develop an S-100 based ENC product specification known as S-101 that is expected to enable updating of symbology, data and software enhancements. The S-101 development is being undertaken over several years and will involve active participation of various stakeholders, including hydrographic offices, ENC software producers, ECDIS manufacturers, mariners, and other maritime users. It is expected that any ECDIS equipment software that is upgraded or reconfigured to use S-101 Electronic Navigation Charts will continue to be able to use the current S-57 Edition 3.1 during the migration. Conformance with ISO/TC211[32] standards allows S-100 to leverage the power of GIS for the hydrographic community by maximizing interoperability with other geospatial data type and platforms. As an industry partner for the design of the S-101 standard, ESRI in partnership with NOAA has developed an IHO S-57 to S-101 converter to support the S-100 Test Strategy Working Group in testing and validating the S-101 standard before it becomes published for the international hydrographic community. This augurs well for a smooth migration from S-57 to S-100 in the future and dovetails with IMO's e-Navigation Strategic Implementation Plan. The SIGRID-3 vector archive format for sea-ice charts is compatible with IHO's S-100 standard.

2.5.4 Limitations: Maritime Charting- Northwest Passage

Navigation in the high latitudes such as the Arctic is a tough job at the best of times. This section will specifically deal with limitations encountered in respect of route modelling in the NWP. Hydrography may be the oldest science of the sea but Arctic waters lack hydrography as well as electronic chart coverage. A comprehensive report from the

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[32] ISO/TC211: Geographic Information Standards

Auditor General, Canada (Govt. of Canada-A, 2016) concluded that Canadian Arctic waters remain inadequately charted to accommodate the projected increase in shipping traffic over the coming years. Canadian Hydrographic Survey reports indicate only 10% (Govt. of Canada-A, 2016) of the Canadian Arctic Waters have been surveyed to modern standards (Appendix 11) that includes the main shipping corridors in the NWP identified in this study. The quality and accuracy of navigational charts depends upon the hydrographic data and methods used to compile them (Appendix 12). The CHS chart catalogue of the Canadian Arctic does contain a few old nautical charts with respect to their publication dates and horizontal datum standards. Some of the charts have depth soundings in fathoms and hydrographic surveys are unreliable at places. The frequency and quality of depth information in the shipping lanes require a lot of improvement for commercial shipping to transit the area. The audit report (Govt. of Canada-A, 2016) observed that 10% of the nautical charts date back to the 1970 or before and only 25 % of the paper charts appear to be of high quality with respect to reference datum to establish position data. This study found gaps in the electronic chart coverage provided by CHS in vast areas of the western Arctic and select areas along the principal shipping lanes (Appendix 13).

2.6 Choice of GIS software and Data format

Spatial Analysis and maritime route network modelling in GIS requires the selection of appropriate GIS software suite among a host of commercial and open source software available in the market. The US National Ice Centre moved towards a GIS production (GRASS software) environment for ice charts in 1996 and subsequently opted for ESRI's

‘ArcInfo’ suite in the late 1990’s (Fequet et al., 2009). The Canadian Ice Service adopted the ArcGIS suite for ice analysis in 2006. The SIGRID-3 files used by CIS contain coastline features derived from the DCW[33] data sets originally created by ESRI in 1993 (Fequet et al., 2009). The US National Snow and Ice Data Centre make use of various GIS software suites including ESRI’s ArcGIS in many of their product offerings. This study finds the ESRI’s ArcGIS software to be the most popular among researchers and national ice centres in North America and elsewhere. Having reviewed the available literature and the elements required for route modelling, the study finds ESRI’s ArcGIS commercial software to be the platform most convenient to attempt the model. The two principal pillars needed for mapping the route network namely, the electronic navigation charts, and the sea-ice datasets are available from CHS and CIS respectively in the desired format. The ArcGIS suite supports both the navigational and ice datasets as reviewed.

2.7 Multi-criteria Decision Analysis in GIS

Spatial decision analysis problems involve a large set of feasible alternatives and multiple evaluation criteria. Most of the time, these are conflicting. Many spatial decision problems such as the maritime route network problem we are addressing gives rise to a GIS based MCDA that aids in the decision-making process. The field of GIS-MCDA has grown considerably in recent years to help decision support capabilities of GIS and related technologies. The integration of GIS and MCDA for decision making in network problems is a unique example of how linking concepts and methods from two distinct

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[33] DCW: Digital Charts of the World

fields can yield solutions to tackling decision problems (Malczewski and Rinner, 2015). As per Faiz and Krichen, (2013); Tong and Murray, (2012), spatial optimization models are best suited to finding a solution to a well-defined spatial problem. The concept of Spatial Decision Support System (SDSS) has been one of the central elements of GIS since the 1990's (Armstrong, Dey and Densham, 1991; Jankowski, Nyerges, Tuthill and Ramsay, 2006; Nyerges and Jankowski, 2010; Sugumaran and DeGroote, 2011). This study has utilized the SDSS concept to determine the layer of 'SNZ' from a number of navigational constraints built around the original layer of S-57 ENC vector data sets. The primary aim of adopting the SDSS is to incorporate the knowledge and experience of experts[34] in ice navigation into computer-aided procedures not only to increase the efficiency of data-processing operations but more importantly to achieve the optimal criterion layer for navigation from data available on the navigation charts. The ability of GIS to handle preferences and judgements (Malczewski et al., 2015) in the planning process is of critical importance and incorporating the rule based expert knowledge technique is one way of conveying information in a computer-aided decision support system such as the CAROM. There are three key elements in any multi-criteria decision problem: decision maker (s), alternatives and criteria (Zarghami and Szidarovszkyet, 2011) and the three core concepts for tackling the GIS-MCDA problems are value scaling, criterion weighting and decision rule (Thill, 1999; Malczewski, 1999).

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[34] Experts: Shipmasters experienced in ice navigation/ Ice Pilots

2.8 Speed Determination in Ice

Determination of speed is one of the most critical elements in ice navigation because sea-ice presents a physical obstacle of varying magnitudes to a ship in motion. Ice avoidance not only enhances safety of the vessel and better speed but also prevents ship maintenance (buckling and hull deformation) and grey water pollution (paint flaking and abrasion) leading to lesser downtime and overall ship productivity. Mulherin, Eppler and Sodhi (1999), while carrying out a sensitivity analysis of environment variables that affect transit speed in the NSR, observed that ice conditions account for two-thirds of the resultant speed. The ice field is usually composed of several ice types varying in concentration and thickness. The thickness of ice, even in the same ice type, exhibits intra-annual seasonal variations and the logged speed tends to be non-uniform and non-linear (Kotovirta, Jalonen, Axell, Riska and Bergelund, 2008) with ice resistance. Furthermore, Maslanik et.al, (2007) and Kwok et.al, (2009) have demonstrated marked seasonal variability in median ice thickness values per ice class (Table 2) in their findings.

Table 2
Median Ice thickness per age Class-Arctic region

			ICE THICKNESS(Cms)			
	First Year		**Second Year**		**Third Year**	
Year	**Feb/Mar**	**Oct/Nov**	**Feb/Mar**	**Oct/Nov**	**Feb/Mar**	**Oct/Nov**
2003	NA	127.6	NA	183.5	NA	225.5
2004	157	117.5	206.1	180	271.7	254.3
2005	169.1	118	215.4	139.6	244.9	204.7
2006	163.6	126.4	178.7	131.6	209.9	164.4
2007	181.9	136.6	187.1	174.1	198.3	183.1
2008	159.7	NA	199.2	NA	187.2	NA
5-Year mean	**166.3**	**125.2**	**197.3**	**161.8**	**222.4**	**206.4**

Note: Adapted from “Projected 21st-century changes to Arctic marine access” by
Scott R. Stephenson, Laurence C. Smith, Lawson W. Brigham, John A. Agnew, 2013, pp38

Furthermore, sea-ice could also be ridged[35] or decayed[36] that may have an additional impact on the speed than in level ice[37]. Ship performance in ice can be judged by the resisting forces provided by sea ice and the propulsive forces generated by the ship’s propulsion machinery. The positive net thrust developed subsequently translates into velocity or resultant speed over the ground. The ice climatology charts predict certain sea ice parameters including the Stage of Development of ice, a proxy for ice thickness in an ice regime. This research considered various methods available for predicting ship speed in level ice. The ship’s power output and associated parameters provide the propulsive forces required, and the ice parameters provide the resistive forces necessary to compute the velocity required. It is important to understand the physical and mechanical properties of sea ice to predict the resistive forces a certain ice type will offer to a ship in motion. The mechanical properties of ice are vastly different from other substances. Aptly termed

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[35] Ridged Ice: A line or wall of broken ice forced up by pressure.

[36] Decayed Ice: Decayed Ice: Ice that has become honeycombed and in an advanced stage of disintegration

[37] Level Ice: Sea-ice unaffected by deformation.

a viscoelastic solid, sea-ice can maintain its strength and brittle behaviour at relatively high temperatures; it is brittle when loaded quickly and ductile when loaded slowly (Daley, 2001). The various factors that influence the measured strength of ice include strain rate, temperature, and grain size. Understanding how sea-ice is acting on a ship forms the basis of the design of ships for ice. The design elements in an ice-capable ship include adequate hull strengthening, sufficient engine power, and ability to withstand operations in extreme weather conditions prevailing in the Arctic (Riska, Tan and Moan, 2013). Good performance is synonymous with better manoeuvrability since no amount of additional hull reinforcements is enough if the vessel cannot manoeuvre in ice. The strength of sea-ice and the compressive power it wields is enormous, and navigation in ice with an ice class vessel is more about tactful and strategic manoeuvring with due respect to the forces of nature. The hull design, propeller design, and thrust are a critical component to minimize propeller-ice interaction (Riska, 2013) and smoother contact with ice rather than a forced entry is, therefore, advisable. The International Code for Ships Operating in Polar Waters (POLAR CODE) provides a mandatory framework for ships navigating in IMO delineated waters of the Arctic (Appendix 14) and Antarctic and is expected to come into force on January 1, 2017. The Polar Code stipulations go beyond the existing requirements of the International Convention for the Safety of Life at Sea (SOLAS), 1974, as amended ("the Convention"), and other relevant binding IMO instruments such as the MARPOL and STCW conventions.

A ship constructed as per IMO Polar Code stipulations is likely to have adequate strength for the approved Polar Class category because the class type is associated with the operative environment of the ship. The ship-owner may specify additional requirements beyond the minimum requirements in some instances, but the shipbuilding yard usually has a free hand in the appropriate design in close cooperation with the ship's classification representative and owner's requirements.

2.8.1 Icebreaking Resistance and Powering Requirements

The general arrangement plan of icebreakers as well as ice-class ships has changed little since the 1970's, the hull and machinery design based on experiences gained from similar ships built earlier. The classification society plays a key role in formulating the structural specifications and maintains a strong oversight of inspections and quality control in the shipyards. The hull shape of icebreakers is characterized by small buttock line angle ($\varphi < 20°$), rounded buttock lines and waterlines and sides inclined to make $\beta > 0$. The principle of hull lines designs has been to make the flare angle ψ as small as possible (Appendix 15). The ship's overall performance in sea-ice is measured by its ability to negotiate various ice regimes with due dispatch, preclude damage to the hull and prevent besetting. Sea- ice resistance depends on the ice properties; the shape of the hull and the thrust furnished by main engine propulsion and can be mathematically calculated and quantified. The manoeuvring performance is determined by transverse forces provided by the rudder(s)/ azipods[38] and the resistance mainly provided by ice, the wind and current to a lesser extent.

A ship breaks the ice by forcing it downwards to break in flexure but tends to slow down as ice gets thicker and the engine load increases. If no action is taken to speed up with

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[38] Azipods: Azimuth thrusters (electric podded)

additional RPM[39] (if available), the ship is brought to a stop and must change to a mode of operation called “backing and ramming” (Daley, 2001). A ship while navigating through ice experiences two kinds of forces, namely the resistance offered by water and sea-ice. Ships cannot operate effectively at very low speeds because the rudder performance suffers and manoeuvring gets sluggish as the rate of advance reduces. Increased ice resistance forces a vessel to lose steerage, manoeuvre effectively, and risk besetting. The rudder responds efficiently only when a reasonable amount of water flows over it, and ships tend to lose steerage as the speed reduces. The process of “backing and ramming” prevents the ice from solidifying around the ship and provides the mechanism to free itself from getting trapped and beset in ice. The Shipmaster must realize this situation early on to avoid being ‘choked’ by ice and should the vessel lose complete momentum, the process to freedom from the ice will get harder and eventually impossible. External help in the form of an icebreaker or the assistance of a passing ship to cut a channel may be necessary which may not be forthcoming very soon in an ice field where open water is at a premium, and the icebreaker may be days away from rendering assistance. Most specialists recommend the use of the model and full-scale data, as well as analytical methods (Colbourne and Daley, 2013) to help estimate the true capabilities of a ship. The analytical methods reviewed in this study include Lindqvist, (1989), Valanto (2009); Su, Riska and Moan, (2011) and Zhou, Peng and Wei (2015). Hanninen (2003) investigated ice load measurements on board ice class tankers while Madsen (2010) investigated results of DNV’s Ice Load Monitoring (ILM) project on board the KV ‘Svalbard’. Numerical methods were preferred as the empirical relationships between

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[39] RPM: Engine revolutions per minute

ship characteristics and ice data are programmable on a computer. This study has adopted the Riska- Lindqvist concept of equating total ship ice resistance to calculate the average speed of the ship in each ice regime as available from CIS SIGRID-3 vector ice datasets. There are numerous predictive models to calculate speed in ice, and further research is required to establish a cogent relationship between speed and ice resistance. Comparison of estimated speed with AIS[40] data from the Baltic Sea (Kotovirta et al., 2008) is a recent phenomenon, and a bigger sample of empirical data is required to study the relationship between ship speed and ice resistance due to the complexities involved in mathematical modelling.

2.8.2 Limitations: Ship-Transit Model

The modified Riska model used in the calculation excludes the ridged ice component in the first Riska methodology devised primarily for Baltic Sea ice where vessels move in a convoy and distances are not as large as the Arctic Ocean. The CIS ice datasets in the current format do not give any ridged ice data for the Canadian Arctic and assumption of a linear relationship between ship speed, and ice concentration may be an oversimplification from the actual and requires further study. The net thrust calculation and the resultant ship velocity derivation ignores other environmental factors that influence ship speed namely current and wind speed and direction. The actual ship speed over the ground is a resultant of all factors that affect speed. The ice thickness calculation from the attribute data tables can be further improved with better consistency and

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[40] AIS: Equipment for ‘Automatic ship identification’ on board ships

description since the missing variable (-9) does not tell much about the stage of development, partial ice concentration, and floe size.

2.9 Economic Viability Model: Cost-Benefit Analysis

Liner Shipping or containerized transport is one of the most efficient modes of transporting goods by sea and has become the global economic engine of transport connecting countries, markets and people this century (World Shipping Council, 2016). The industry has undergone a paradigm shift in the last decade that has witnessed mega containerships flooding the market despite the global economic downturn seen in the same period resulting in excess shipping tonnage. Currently a prolonged global trade slowdown and excess slot[41] capacity are the likely cause of a weak freight market, and volatile shipping rates.

Sea-ice decrease across the Arctic region is a reality, and maritime transport is a logical consequence projected to grow this century. Nevertheless, what are the risks involved in ice navigation and how could this be mitigated given the fact that ship-sourced pollution is of utmost concern and ship traffic is projected to increase with diminishing sea-ice? Are the ship and the shipboard management/ice-navigator well equipped to conduct a safe and efficient passage through the Arctic, given all the challenges of infrastructure, international regulatory framework, training, and technology? The above concerns formed the cornerstone of the research proposal submitted by the author to carry out a study seeking to develop a Computer -aided Arctic Route Optimization Model (CAROM) that may serve as a tactical and operational response tool to conduct voyage planning during ice navigation. The model may also be able to predict a time of transit useful to a Cost-Benefit Analysis of the route in comparison to the Panama Canal route for a

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[41] Slot capacity: Container (TEU) carrying capacity

container ship trading between ports in NE Asia and NW Europe. The word ‘operational’ signifies practically useful on board during navigation and ‘tactical’ refers to voyage planning with due regard to changing ice conditions during the transit through the ice. There have been some simulation studies conducted in the last 20 years on topics ranging from economic viability aspect of Arctic Shipping Routes (NSR, NWP, and TPR) to increased access for ship navigation including a 3D GIS mapping of the NSR (Chang, Hey, Chou, Kao, & Chiou, 2015) with widely divergent conclusions (Pruyn, 2016; Lasserre, 2014). Almost all the studies reviewed in this paper (1996-2015) focus on the economic viability aspect of the NSR (Mulherin et al., 1996; Srinath, 2010; Wergeland, Ostreng, Eger, Mejlander-Larsen, Floistad and Lothe, 2013; Chang, Hey, Chou, Kao and Chiou, 2015). One of the papers reviewed (Choi, Chung, Yamaguchi, & Nagakawa, 2014) used a novel approach to the economic viability aspect in both the NSR and the NWP by Arctic sea route path planning based on an uncertain ice prediction model. A few devote their efforts to simulations in the NWP (Somanathan, Flynn and Szymanski, 2008; Wergeland et al., 2013) with an empirical derivation based on a comparison of distance between ports in NE Asia and NW Europe/ECNA[42]. The associated assumptions and metrics (technical and economic) calculate and compare Voyage Costs, Capital Costs, and Operating Costs set up against the distance traversed via the Arctic (NSR/NWP) and the two Canals (Suez and Panama). Some of the parameters namely, average speed in the Arctic segment, the load factor (container shipping) and the insurance premiums differ widely in their assumptions which are expected to some degree due to lack of credible commercial shipping in the Arctic in general and NWP in

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[42] ECNA: East Coast America

particular. Due to lack of a methodical speed calculation approach in the ice-bound segment, the time estimation in the Arctic leg of the route is approximate at best.

The Peel Sound passage in the southern portion of the NWP is the longest route; shallow in some areas for large ships but relatively easier on sea ice impedance when compared to the more northerly M'Clure Strait and the Prince of Wales Strait routes. The northern portion of the NWP has a challenge with Multi-Year Ice (MYI) drifting in from the Central Arctic that the southern route does not to have. Which route should the vessel follow in ice given the three alternatives provided the ship had a safe UKC[43] to proceed in either one of them but had the sea-ice barrier to overcome? A path of least resistance unique to the vessel may give an answer to the above. How should a ship plan for an icebreaker escort if expected to encounter negative Ice Numerals based upon the AIRSS/POLARIS (section 3.3.2/3.3.4) decision support approach? The CAROM outputs result in preparation for contingency well in advance of the vessel arriving in the area with negative Ice Numerals. The NWP segment requires being meticulously managed to assess the economic viability of the entire trans-Arctic route that includes voyage calculation for the open water ocean routes in the Atlantic and Pacific segment (Figure 3).

Somanathan et al., (2008) have modelled container-shipping routes through NWP using historical ice data (1999-2003) from CIS archives. Would the model be more realistic if route optimization is conducted with the latest available ice datasets such as weekly or daily ice charts, if available? Technological advances in satellite communication such as large bandwidth and affordable satellite data costs make this a reality in the Arctic like

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[43] UKC: Under keel clearance (charted depth in relation to draft of ship)

any other ocean region. CIS does publish ice datasets on a weekly basis for the Canadian Arctic that underpins this research. Is it more practical to develop the model with the actual Electronic Navigation Charts as a base layer for spatial analysis and route modelling albeit on a personal computer in a non-navigational environment? The ships are already using the Electronic Navigation Charts on the ECDIS and the ice analysis charts provided by CIS is received via facsimile receiver onboard. Some research papers have analysed ship transits in the NWP (Judson,1997; Mudge, Fissel, Alvarez and Marko, 2009) while others have analysed Global Climatic Models (GCMs) to predict spatiotemporal sea ice ablation and maritime access in the Arctic this century (Stephenson, Smith, Brigham and Agnew, 2013; Smith and Stephenson, 2013; Wang and Overland, 2012). The two most prominent GCMs used for studying the Arctic ice climatology being the CCSM4[44] and the CMIP5[45]. A computer based route optimization system 'View Ice' tested in the Baltic Sea and validated with AIS data (2005-2007) had its challenges to contend with due to short route segments (50 NM to 350 NM) and icebreaker assisted convoy operations.

Arctic ice navigation involves independent navigation and voyage planning for considerable distances that could include a passage up to 2400 NM (Lancaster Sound to Bering Strait via Peel Sound passage). The entire passage may last more than ten days depending on ice conditions and season of transit (Lasserre, 2014). A computer based route planning simulation in public 3D GIS (Chang et. al, 2015) using Google Earth was

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[44] CCSM4: Community Climate System Model version 4

[45] CMIP5: Coupled Model Intercomparison Project, Phase 5

employed to conduct a cost efficiency of using the NSR as compared to the Suez Canal between major ports in Asia and Europe. This research paper is proposing GIS-based route optimization using ENCs and CIS ice charts followed by a Cost Benefit Analysis of the NWP vs. Panama route. The goal of both the studies may be similar but the approaches differ.

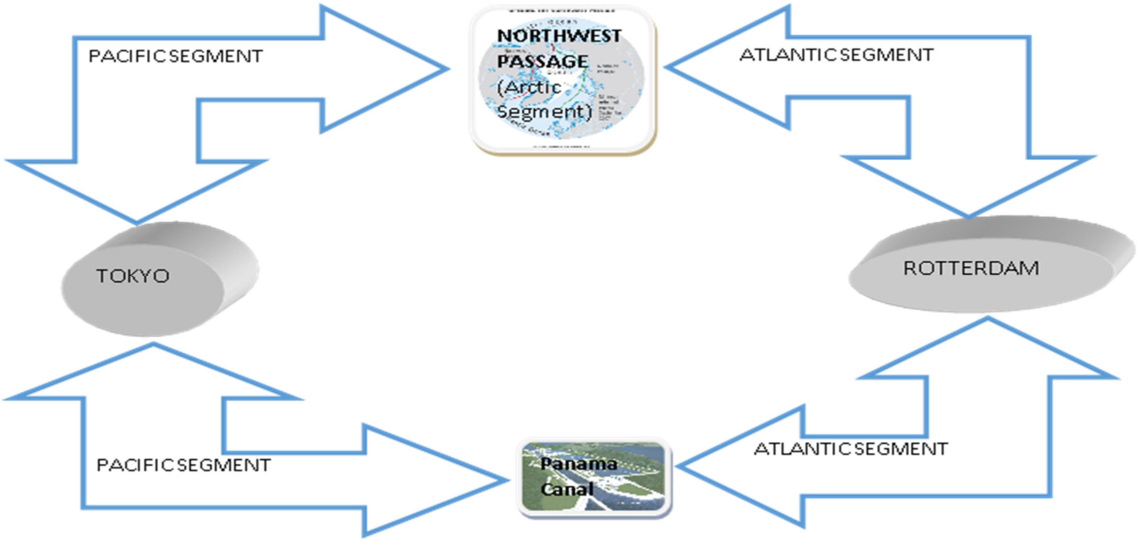

Figure 3: *Schematic view: Trans-Arctic shipping route (via NWP)*

Source: Author

The study will conduct a Cost-Benefit Analysis and cost comparison of operating containerships via the Panama Canal and the Northwest Passage (seasonal) between

Tokyo and Rotterdam. Such an approach has been used (Lasserre, 2014) by a few other researchers with different methods to calculate the ice-bound segment (NWP) of the route. Bunker fuel costs alone account for the largest share among the Voyage Costs ((Stopford, 1997) a ship owner should budget for as prices depend on the supply and demand situation and mirror the crude oil price swings in the global market. Somanathan et al., (2008) for instance, have taken historical ice data and year-round transit instead of a seasonal transit in the NWP to arrive at the 'Required Freight Rate' (RFR). The seasonal transit method would use the current sea ice data and as such may predict a much better transit time in the NWP than historical ice data. The Cost Benefit Analysis as proposed in this study makes the overall cost calculation much more practical for trans-Arctic container ships trading between ports in NE Asia and NW Europe. A comparison between a low bunker price scenario and a high bunker price scenario is carried out for the two ship sizes and the two routes (Panama Canal and NWP) to test for any significant variation in the Required Freight Rate.

2.9.1 Limitations: Cost-Benefit Model

The proposed Cost-Benefit Model involves various assumptions based upon the current commercial trends in the Container shipping trade. The independent variables include average load factor, fuel consumption and bunker fuel price for a hypothetical Panamax and a Neo-Panamax vessel. The average load factor is extremely sensitive to the overall cost estimation and remains an unknown quantity for the NWP route due to a two-port rotation. There are no trans-shipment ports factored for the NWP route. Insurance costs for the NWP segment are estimated due to lack of shipping data on this passage. The assumption that the ships will use a uniform grade of fuel while transiting both routes may not be the case for the Arctic segment as some researchers have noted (Lasserre, 2014). The load factor on the Panama Canal route assumed at 80% as the best estimate average, although there may be seasonality swings and container imbalance factors that may change with supply and demand dynamics. The introduction of the hypothetical Neo-Panamax container ship through the NWP is a novel concept that the study considers due to the recently widened third set of locks in the Panama Canal. The speed over ground achieved by a ship (PC-4) in open water steaming is the net result of engine power (forward thrust) and meteorological forces such as current, swell and wind. The same ship must surmount level ice resistance in addition to the forces of wind and current (assuming same as open water) to log a similar ground speed in ice covered waters. Higher fuel consumption is anticipated for the ice bound segment, other things being equal. Moreover, the fuel consumption in case of the ice classed (PC-4) ship may add an additional factor of uncertainty in the fuel consumption when compared to the non-ice classed container ship of the same size. The fuel consumption is assumed to be uniform across both vessel classes irrespective of open water or ice navigation resulting in an approximation in the Cost Benefit Analysis.

2.10 Voyage Planning in NWP: Proposed Solution in GIS

While every study contributes towards dissemination of knowledge, the Computer-aided Arctic Route Optimization Model (CAROM) may fill up the desired gap as a practical and operational solution to route planning and decision making in ice covered waters (Figure 4). The data input used to construct the model is familiar to ship navigators who use the hard copy paper format on board ships as a routine. The proposed computer-aided route analysis aims to ensure the end output is an optimized route in a digital format easily shared with multiple users (shipping company, charterers etc.) and communicated on board to the end user via satellite link. The waypoints so obtained not only prepare in voyage planning, but contingency plans involving icebreaker support may be determined well in advance since the system uses the AIRSS/POLARIS (section 3.3.2/3.3.4) evaluation criteria to calculate the Ice Numerals based on the latest available CIS ice charts.

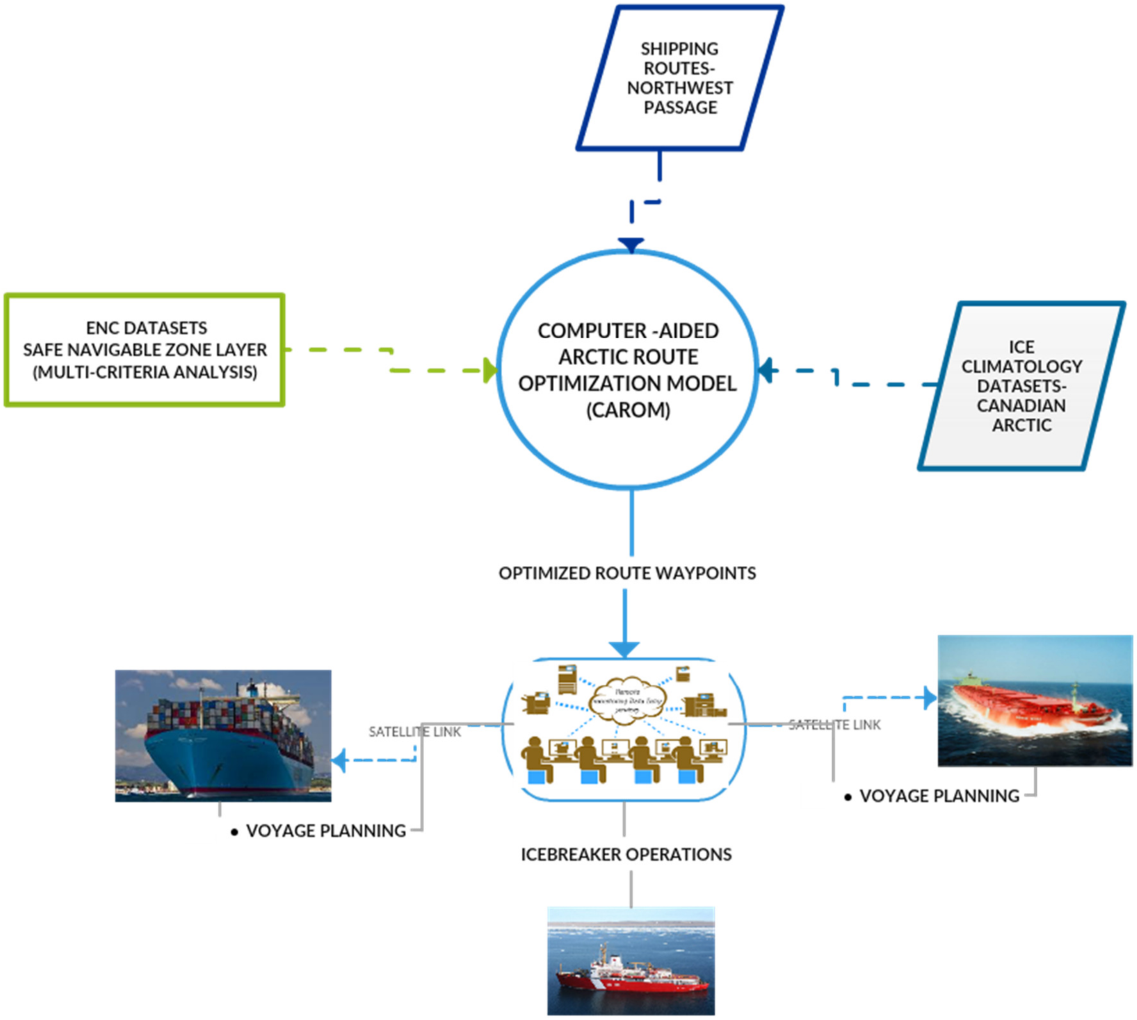

Figure 4: *Computer-aided Arctic Route Optimization Model (CAROM)*

Source: Author

Speed-in-ice plays a vital role in establishing a hierarchical approach to the path of least resistance along the route and a methodology to estimate the same from the ice datasets is necessary. The study envisages the determination of a ‘Safe Navigation Zone’ in the NWP by applying expert knowledge techniques to predict optimized shipping routes among a set of alternative routes. The ice charts overlain on the ‘SNZ’ layer are used to find the path of least resistance in ice covered waters with speed inputs from the Ship-Transit Model. The tools used to construct the CAROM include the relevant ENCs, the three shipping routes in the NWP, the CIS ice charts and the ArcGIS suite for spatial analysis, digital cartography and route prediction.

2.11 Summary of Research Literature and Gaps

The chapter reviewed existing literature on currently available navigational and ice data and the digital platform to conduct spatial analysis and route modelling in GIS. The study found only one instance (Chang et. al, 2015) of literature that specifically addresses a maritime route optimization model using GIS, although Google Earth is used for navigation and a high -geometry maze router with weighted regions implemented to conduct route optimization in the Northern Sea Route.

The proposed research objectives are unique due to the sheer breadth of related literature needed to conduct an interdisciplinary study of this nature. A creative thought process to interface the various branches of science is necessary to develop the proposed models. Digital maritime chart data is required to conduct spatial analysis besides the ice datasets of the Canadian Arctic provided by CIS. ESRI’s ArcGIS suite is the software of choice for the reasons outlined in this chapter. The Northwest Passage has significant gaps in charting and hydrographic surveying that affects the quality of chart content on the electronic navigation charts. The economic analysis model literature reviewed for the last two decades does not provide a robust way to calculate the transit time in the NWP segment. A simple distance calculation and an assumed average speed in ice may not give an accurate time of passage through the ice. The ‘Required Freight Rate’ computation methods reviewed is a ratio of the estimated costs in the open water segment (Atlantic and Pacific Oceans) and the ice segment (NWP) to the total number of containers (TEU) transported per year. The calculation of transit time in ice covered waters, although mentioned in some studies does not provide any insights into solving the ice route segment separately. The proposed Route Model will determine the actual distance sailed in the NWP besides the time of transit and use the Riska method for Ship-Transit Modelling. The Riska method as explained earlier, in Baltic Sea ice transits is a practical approach and requires minimal assumptions to calculate ice resistance. Almost all the data needed in the formulae is available from shipyard plans of the ship in questions besides the known constants. The ‘RFR’ approach for the CBA focuses on the ‘cost’ side of cash flow analysis and does not depend on volatile freight rates to estimate profitability margins. The next chapter delves in the methodology required to assemble the ‘tool box’ necessary to develop the route model.

Chapter 3: Research Methodology

3.1 Introduction

It is evident from the literature review that an interdisciplinary approach is required to achieve the stated research objectives. The relevant data might not be full of the desired quality but is currently healthy enough to devise a prototype route model using the existing software tool ArcGIS. The navigational and ice datasets are available in vector format; a workable method is at this moment required to bring all the elements on a common platform to conduct spatial analysis in ArcGIS. The CAROM requires the ship transit-in-ice model for the speed input to compute the waypoints for the optimized route determination. The two models may provide the desired 'least cost' route and a solution to the transit time in ice that will enable a comparative economic analysis of the trans-Arctic shipping route as envisaged. A robust methodology is required to achieve the stated research objectives. Re-routing based on changing ice conditions require the frequency of ice data transmissions to go up significantly in the future. Evolving technology and availability of appropriate satellites with the spotlight on the Canadian Arctic is necessary to conduct effective voyage planning in ice.

3.2 Shipping Corridors and Navigable Routes-Arctic Region

For this study, a Shipping Corridor is a passage connecting the two extremities of the Arctic Ocean that join the Atlantic and the Pacific Ocean. The three distinct passages (Smith and Stephenson, 2013) identified in the Arctic region (Appendix 16) are the Northern Sea Route (NSR), the NWP and the route through the Central Arctic, popularly called the Trans-Polar Route (TPR).

The NSR is the name given to a set of shipping routes in the Russian Arctic joining the Bering Strait and Kara Gate. The NWP joins the Bering Strait to the eastern seaboard of Newfoundland via the Canadian Arctic Archipelagic (CAA) territory. The TPR connects the Bering Strait with the shipping lanes on the north- western coast of Norway via the Central Arctic. Both the NSR and the NWP shipping corridors have a number of navigable shipping routes (Wergeland et al., 2013) that leaves an alternative passage for icebound ships in the Arctic Ocean frequented by adverse weather conditions, short daylight and above all sea ice and icebergs to negotiate. Climate-induced change in sea ice concentration and thickness is vastly changing the technical feasibility of Arctic ship navigation for the better. The GCMs project longer summer season and gradually diminishing ice across the Arctic by the middle of this century (Smith and Stephenson, 2013). The Arctic Transportation Accessibility Model (ATAM) projects commercial shipping to commence between 2040 and 2059 in the NWP (Appendix 16). The ATAM projects September navigation in the NWP by ‘PC-3’, ‘PC-6’, and ‘OW’ vessels assuming various climate-forcing scenarios. This study has identified three navigable routes in the Canadian Arctic (Figure 5) that ships of various draft and disposition may be able to use.

The three routes identified in the NWP are:

- The M’Clure Strait (MS) route
- The Prince of Wales Strait (POWS) route
- The Peel Sound (PS) route

The ‘MS’ route is the widest among all three routes as it exits the NWP (north of Banks Island) and a bit longer (948 NM) than the ‘POWS’ route (941 NM). One cannot predict the quantum of ice drift (dependent on current and wind direction) and the ensuing ice accumulation in parts of the M’Clure Strait with precision that introduces an element of uncertainty regarding a convenient and fruitful transit through the NWP. Liner shipping companies (container shipping) do not prefer delays due to commercial reasons and prior scheduling commitments. Even though the ‘MS’ route is considerably shorter than the ‘PS’ route (1282 NM), the presence of MYI adds to the uncertainty and the overall cost of the transit. The ‘POWS’ route provides the shortest route alternative, but the vessel does have to pass closer to the coast (Victoria Island) in restricted waters, unlike the expansive ‘MS’ route. The ice regime is generally more favourable in the ‘POWS’ and thus offers a good alternative of a safe passage short of an icebreaker escort, should the M’Clure Strait be blocked with MYI.

The Canadian Arctic Archipelagic area provides a somewhat more diverse routeing scenario with alternative routes and complex sea-ice climatology. The Northwest Passage is thus, seen as a more challenging region to model, but offers a series of route alternatives for ships. This study has thus concentrated on developing a prototype model for the NWP with the expectation that a model that worked for this area would be more easily adaptable to other ice prone shipping regions including the NSR or the Trans-Polar Route.

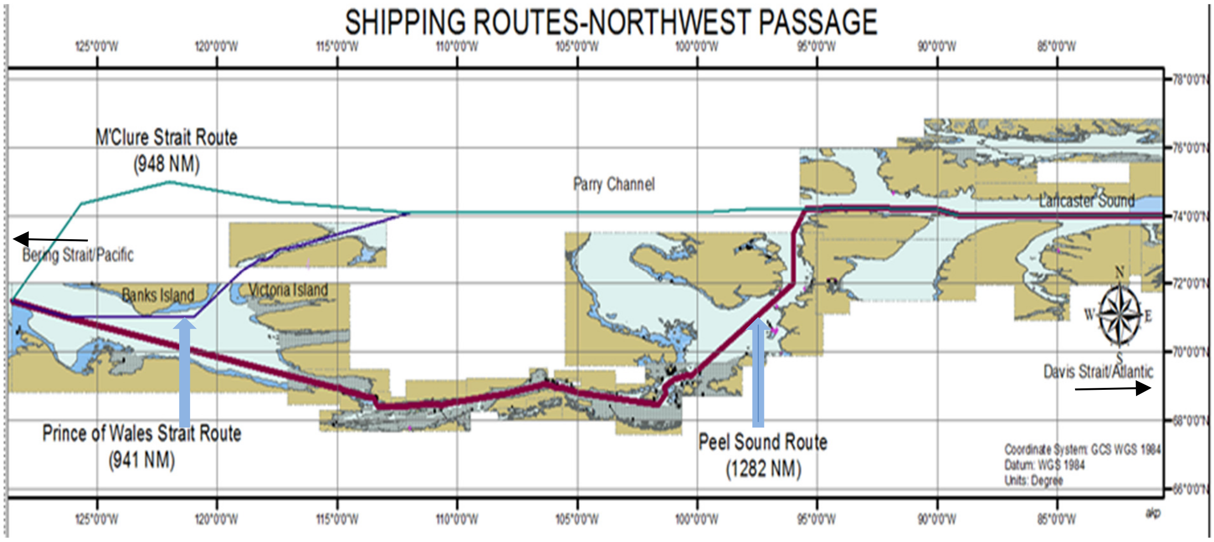

Figure 5: *Shipping Routes-Northwest Passage*

Source: Author

A Neo-Panamax Container vessel (draft 15 meters) may navigate with a safe under keel clearance on both the 'MS' and 'POWS' routes as per nautical charts published by CHS (Fisheries and Oceans Canada-C, 2016). The 'PS' route passes through a number of narrow passages particularly in the Victoria Strait and the Coronation Gulf before meeting the Amundsen Gulf but is deep enough for a Panamax container vessel (draft 12 meters). The ice regime along this route is generally more favourable and currently the most popular route for intra-Arctic traffic and resupply ships in the Canadian Arctic. Extreme caution is warranted due to the presence of ice in narrow and relatively shallow areas. A close-up analysis of all the three routes indicates that the 'POWS' route may be the best alternative for trans-Arctic vessels of all sizes and ice types mentioned in this study.

3.3 Route Selection and Optimization

Evaluating and selecting the most suitable navigable route is of tactical and strategic importance in navigation and existence of alternative passages provide the much-needed flexibility that the Canadian Arctic Archipelagic area presents. Strategic and tactical navigation is referred to voyage planning in open water and ice-infested waters respectively as explained in section 3.5.2.

Proper route selection and speed of advance in ice-infested waters may be one of the most critical decisions an ice navigator must make during the entire voyage that can result in success or failure with catastrophic consequences at times. Improper route selection in ice may cause lengthy delays, costly ship-repair, and even abandonment in an area where appropriate maritime infrastructure such as proper docking and repair facilities are inadequate for commercial shipping. Appropriate route selection holds true for vessels navigating in almost all regions of the Arctic, and a proper assessment of the ice regime and an underpinning knowledge of sea ice data, analysis, and voyage management is critical.

This study investigates and analyses the three identified routes in the NWP shipping corridor using the concepts of Multi-criteria Decision Analysis to determine the ‘SNZ’ layer with the exclusion or ‘no-go’ areas built in the model. The parameters for exclusion zones (buffers) depend on the risk profile preferred by the Shipmaster/navigating officer for the vessel in question. A ‘Route’ analysis is subsequently conducted in ArcGIS with the sea ice data acting as an impedance of varying magnitude to surface navigation. The scale of the ice impedance is a function of the total ice concentration, partial ice concentration, the stage of development, and the form of ice. The ‘Route’ solver application is a distance analysis tool in ArcGIS ‘Network Analyst’ extension that determines the ‘least cost’ path between a geo-referenced source and destination.

3.3.1 ‘Zone/Date’ System

Shipping Safety Control Zones that make use of a ‘Zone/Date’ matrix that specifies entry and exit dates for various ship types and classes regulate navigation in the Canadian Arctic. The waters are divided into 16 zones where Zone1 has the most severe ice conditions (Appendix 17) and Zone 16 the easiest ice regime to negotiate. It is a rigid system based on the premise that nature follows a regular pattern year after year. This premise does not seem to hold in the current climate change scenario witnessed in the Arctic.

The ‘Zone/Date’ Control table specifies the date of entry and exit; a ship type may use while navigating in a Zone. The input and output matrix is tabulated with respect to the ship category (‘Arctic Class’ and ‘Type’) from Arctic class 10 to Arctic Class 1 (9 classes) plus five categories of ‘Type’ vessels from Type A to Type E. The Arctic Class has since been replaced by four categories (Canadian Coast Guard-B, 2013) termed Canadian Arctic Class (CAC) vessels ranging from CAC1 to CAC4. The CAC4 is equivalent to Arctic Class 3 (Transport Canada-B, 2010) that implies a PC4 vessel in the IMO Polar Code nomenclature. The ‘Zone/Date’ System has one major drawback – since ice conditions vary significantly from year to year, therefore, in a severe year, an amateur operator might attempt a voyage well beyond the capabilities of the ship. In a light ice year, the rigidity of the regulatory system may prevent ships from transiting areas that could be entirely free of ice ((Transport Canada-A, 2010). An example of a PC4/CAC4/Arctic Class3 vessel explains the above point if the ‘Zone/Date’ matrix is followed strictly: In the context of the Northwest Passage, the ‘MS’ route passes through Zones 13, 6, 2, 1 and 4 from Lancaster Sound to M’Clure Strait irrespective of the year. A PC4 ship intending to take a voyage that starts on June 30 is able to enter the Lancaster Sound (Zone 13) but not permitted in Zone 6 (Parry Channel) before August 1 and cannot enter Zone 2 and Zone 1 (M’Clure Strait) before August 20 (Appendix 18) without regard to the actual ice conditions on that day. The matrix puts a severe restriction on the commercial transit of ships even though they may comply with strength criteria and if one considers, the entire route to resemble Zone1 for a moment, the navigation window is only available between August 20 and September 15, a mere 25 days per year. The navigation window for a Type ‘C’ vessel shows that the ship cannot proceed through the ‘MS’ or the ‘POWS’ route at all, irrespective of the season since a major part of the route lies in Zones 1 and 2. Some portions of the ‘PS’ route lie in Zone 6 that implies a one-month navigation window (August 25-September 25) for a part of the NWP. The assumption of fixed schedules irrespective of current ice conditions in the ‘Zone/Date’ may hold an advantage for some shipping operators, but this does not seem to be a practical solution for commercial transit shipping as the above examples prove.

The Canadian Arctic Ice Regime Shipping System (AIRSS) developed through the joint work of government and industry and introduced in 1996, is a more flexible and safe system (Transport Canada, 1997) intended to replace the ‘Zone/Date’ system shortly. The new ships built to CAC standards have the advantage of using both the ‘Zone/Date’ and the AIRSS in the transition period.

3.3.2 Arctic Ice Regime Shipping System (AIRSS)

The AIRSS emphasizes the responsibility of the Shipmaster for the safety of the ship and provides a more flexible framework to assist in decision-making. It requires a higher level of experience for ice navigators, and full use of available ice information. By using the system, the operator has broad discretion in the planning and execution of Arctic voyages. A transitional phase is currently in operation where the ‘Zone/Date’ system and the AIRSS are in use. Once the transitional phase is completed, the Shipmaster as an ice navigator or with the assistance of one (ice advisor), will be responsible for interpreting the existing and forecast ice conditions for safe navigation and passage planning (TP12259E, 1996). Outside the Zone Dates, ships using the Arctic Ice Regime Shipping

System may only enter an ice regime when the Ice Numeral[46] is equal to or greater than zero. The AIRSS regulations require that the decision to get into an ice regime be dependent on the Shipmaster's assessment that the ship can navigate safely through the ice regime. The gradual phasing out of the 'Zone/Date' system would put additional responsibility on the Shipmaster/ice navigator in the safe conduct of the passage while in the Canadian Arctic. The micro-management of the route to follow would involve calculation of Ice Numerals for each ice regime along the passage. Sea-ice is also subjected to spatial and temporal physical change as the ambient conditions of temperature, wind velocity, and direction changes. The physical characteristics of an ice regime such as Thin First-Year Ice may be different at -1ºC when the voyage started than at -30ºC a couple of hours later in the same ice regime.

The Shipmaster may have to frequently adjust course and speed at short distances to reduce engine load and hull stresses brought about by dynamic ice loads in changing ice regimes due to extreme temperature variations. The determination of estimated speed in each ice regime is of utmost importance to achieve a balance between the safety of the ship and delay caused by reduced speed. The shortest passage may not be the optimal route to follow if the ship gets buckling hull damages or even beset while in ice. The ice regime happens to be the most critical factor in charting a course besides adequate depth of water and charted dangers.

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[46] Ice Numeral: A derived number based upon ship's ice class and stage of development of ice. If IN<0, ship may not enter unescorted.

3.3.3 Ice Numerals-Decision Making in Ice

The AIRSS architecture compares the actual ice conditions along a route to the structural capability of the ship. The basic definition of ice regime as per AIRSS is "*an ice regime is composed of any mix or combination of ice types, including open water. An ice regime occurs as a region in navigable waters covered with generally consistent ice conditions; i.e. the distribution of ice types and concentrations does not change very much from point to point in this region.*" (Transport Canada, 2015). Every ice type (including Open Water) has a numerical value that is dependent on the ice category (ice-class or Type) of the vessel. This number is the Ice Numeral (IN). The value of the 'IN' reflects the level of danger that the ice type poses to the category of ship. A vessel may not enter an ice regime if the 'IN' is negative without an escort or as advised by the authorities. The 'IN' for an ice regime is the sum of the products of ice concentration, in tenths, of each ice type and the Ice Multiplier. The Ice Multiplier table is prepared by AIRSS for seven ship classes (CAC)[47] and nine ice types ranging from 'Open Water' (OW) to Multi-Year Ice. The Polar Class equivalence for the ships as determined by the Transport Canada (Transport Canada, 2013) is given in the modified ice multiplier table. Transport Canada introduced AIRSS whereby vessels could navigate in ice-infested waters based upon a mathematically derived 'IN' that is a function of the ship's ice classification, the thickness of ice and ice concentration. Vessels are advised not to proceed unescorted in areas with negative ice numerals (IN<0). The Ice Numeral is derived from the formula:

$$IN = (C_a * IM_a) + (C_b * IM_b) + (C_c * IM_c) + \dots\dots\dots\dots\dots + (C_n * IM_n)$$

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[47] CAC: Canadian Arctic Class

Where:

C_a = ice concentration in tenths of type ‘a.'

IM_a= ice multiplier of ice type ‘a.'

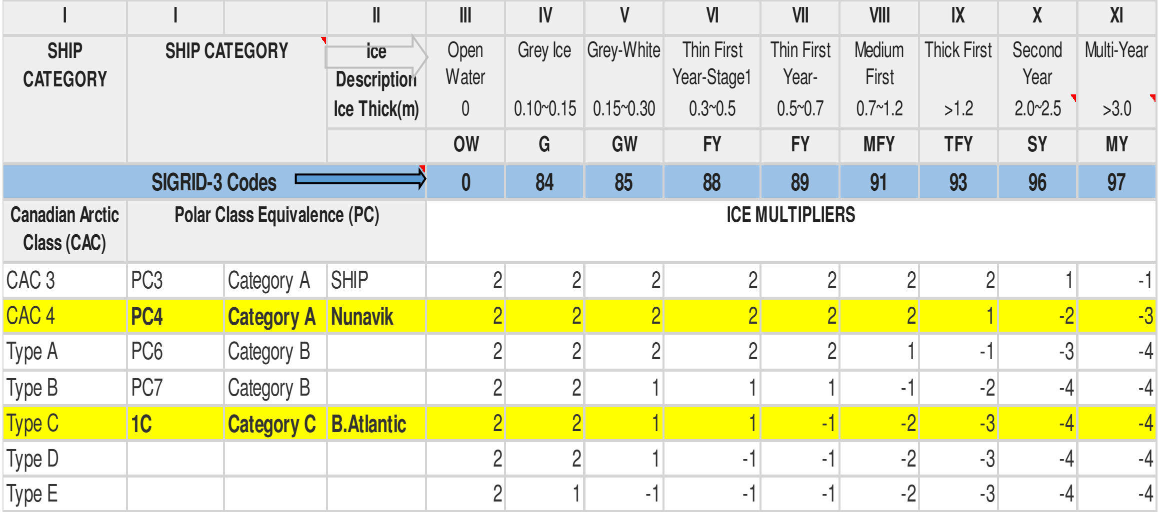
C_n= ice concentration in tenths of type ‘n.'

IM_n= ‘Ice Multiplier’ of ice type ‘n.'

The ‘Ice Multiplier’ is a numeral between + 2 and - 4 across eight ice categories (Grey Ice-MYI) plus open water (OW) and seven ship categories (CAC ice classification) as per the AIRSS ‘Ice Multiplier’ table (Table 3) with the Polar Class equivalence and SIGRID-3 codes added. The Ice Numeral is, therefore, unique to the specific ice regime and a decision-making tool for route selection in the NWP. The route optimization model has utilized the AIRSS concept in the NWP for two categories of vessels namely the Polar ‘Type A’ (PC4) that corresponds to the ‘CAC-4’ and Polar ‘Type C’ (1C) vessel equivalent to Canadian ‘Type C’ ship (Appendix 19).

Table 3

Ice Multiplier Table (AIRSS)



I	I		II	III	IV	V	VI	VII	VIII	IX	X	XI
SHIP CATEGORY	SHIP CATEGORY		ice Description Ice Thick(m)	Open Water 0	Grey Ice 0.10~0.15	Grey-White 0.15~0.30	Thin First Year-Stage1 0.3~0.5	Thin First Year- 0.5~0.7	Medium First 0.7~1.2	Thick First >1.2	Second Year 2.0~2.5	Multi-Year >3.0
				OW	G	GW	FY	FY	MFY	TFY	SY	MY
	SIGRID-3 Codes			0	84	85	88	89	91	93	96	97
Canadian Arctic Class (CAC)	Polar Class Equivalence (PC)			ICE MULTIPLIERS								
CAC 3	PC3	Category A	SHIP	2	2	2	2	2	2	2	1	-1
CAC 4	**PC4**	**Category A**	**Nunavik**	2	2	2	2	2	2	1	-2	-3
Type A	PC6	Category B		2	2	2	2	2	1	-1	-3	-4
Type B	PC7	Category B		2	2	1	1	1	-1	-2	-4	-4
Type C	**1C**	**Category C**	**B.Atlantic**	2	2	1	1	-1	-2	-3	-4	-4
Type D				2	2	1	-1	-1	-2	-3	-4	-4
Type E				2	1	-1	-1	-1	-2	-3	-4	-4

Note. Adapted from Canadian Hydraulics Centre report, “Scientific Analysis of the ASPPR Hybrid System for Type B Vessels,” by Timco, Collins and Kubat, 2009, pp10

Negative ‘IN’ regimes are considered ‘no-go’ areas and programmed as ‘restrictions’ and the positive Ice Numerals considered as ‘barriers,' the degree of impedance being inversely proportional to the speed in ice. CIS ice charts do not model pressure ridging and decayed ice in the current suite of products, hence excluded from the ambit of resistance calculations in the ship transit model signifying a weakness in the model.

The AIRSS system does have its operational limitations, however, on several factors including ice concentration, ice type, and quantification of ice thickness among certain ice types (Thick First Year- Multi-Year Ice) among others. The concept of icebreaker escorted operations and how should the escorted ship adjust its Ice Numeral in assisted convoys are some of the tactical and operational dimensions that a novel operational risk assessment tool called POLARIS[48] is expected to usher in.

3.3.4 Polar Limit Assessment Risk Indexing System (POLARIS)

The draft Polar Code as adopted on 21 November 2014 (IMO- Draft Polar Code, 2014) stipulates additional guidance (Part I-B) in the form of limitations for operating in ice. Shipping companies and other maritime stakeholders have long felt the need to have a link between the ice classification of the vessel (Table 4) and the various ice regimes it may be operating during the year. An IMO constituted technical group led by the IACS has proposed a Risk Indexing System (POLARIS, 2014) with a goal to develop a decision-making system that can be used for voyage planning or in ‘real-time’ navigation from the ship’s bridge. The risk assessment philisophy for ‘real-time’ navigation implies actual ice conditions by visual observation, ice class, and operational mode (independent operation or icebreaker escort). The basis of POLARIS is an evaluation of the risks posed to the ship by ice conditions using ice descriptions consistent with WMO nomenclature and the ship's assigned ice class consistent with the ice classes referenced in the draft Code.

---

[48] POLARIS: Polar Operational Limit Assessment Risk Indexing System

Table 4

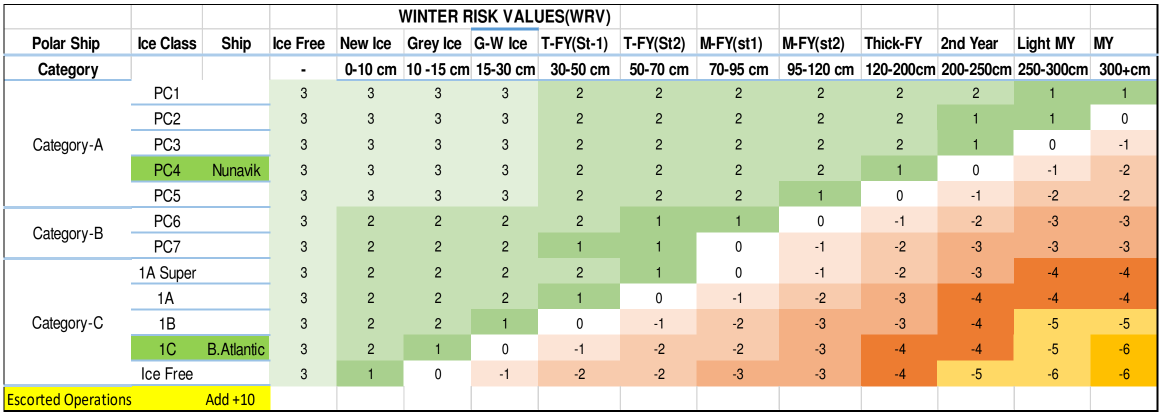
IMO- Polar Classification of Ships

Polar Class	Ice Description*
PC1	Year -round operation in all Polar waters
PC2	Year -round operation in moderate multi-year ice conditions
PC3	Year -round operation in second -year ice which may include multi-year ice inclusions
PC4	Year -round operation in thick first-year ice which may include old ice inclusions
PC5	Year -round operation in medium first-year ice which may include old ice inclusions
PC6	Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC7	Summer/autumn operation in thin-first year ice which may include old ice inclusions
*	Based on WMO sea ice nomenclature

Note: Adapted from IACS "Requirements concerning Polar Class," retrieved May 10, 2016, from http://www.iacs.org.uk/document/public/Publications/Unified_requirements/PDF/UR_I_pdf410.pdf

POLARIS uses a Risk Index of Risk Values (RVs) which are assigned to a ship based on the ice class. The RVs may be used to evaluate the limitations of the ship operating in an ice regime using input either from historic or current ice charts or in real time from the bridge of the ship. The POLARIS uses the partial ice concentration approach to predict Winter Risk Values (WRV) for winter navigation (Table 5) based on ice classification and thickness. The POLARIS architecture makes an important distinction between voyage planning and real-time navigation for an escorted ship as far as the risk-value (RV) calculation methodology is concerned. The escorted vessel must add ten (+10) to its RV during voyage planning to cater for icebreaker assistance. For real-time bridge navigation, the escorted ship visually assesses the ice regime made by the icebreaker track with POLARIS and calculates the RIO[49] based on its ice class that requires the Shipmasters of both the icebreaker and the escorted ship to be in close cooperation.

Table 5
Winter Risk Values



				WINTER RISK VALUES(WRV)										
Polar Ship	**Ice Class**	**Ship**	**Ice Free**	**New Ice**	**Grey Ice**	**G-W Ice**	**T-FY(St-1)**	**T-FY(St2)**	**M-FY(st1)**	**M-FY(st2)**	**Thick-FY**	**2nd Year**	**Light MY**	**MY**
Category			**-**	**0-10 cm**	**10 -15 cm**	**15-30 cm**	**30-50 cm**	**50-70 cm**	**70-95 cm**	**95-120 cm**	**120-200cm**	**200-250cm**	**250-300cm**	**300+cm**
Category-A	PC1		3	3	3	3	2	2	2	2	2	2	1	1
	PC2		3	3	3	3	2	2	2	2	2	1	1	0
	PC3		3	3	3	3	2	2	2	2	2	1	0	-1
	PC4	Nunavik	3	3	3	3	2	2	2	2	1	0	-1	-2
	PC5		3	3	3	3	2	2	2	1	0	-1	-2	-2
Category-B	PC6		3	2	2	2	2	1	1	0	-1	-2	-3	-3
	PC7		3	2	2	2	1	1	0	-1	-2	-3	-3	-3
Category-C	1A Super		3	2	2	2	2	1	0	-1	-2	-3	-4	-4
	1A		3	2	2	2	1	0	-1	-2	-3	-4	-4	-4
	1B		3	2	2	1	0	-1	-2	-3	-3	-4	-5	-5
	1C	B.Atlantic	3	2	1	0	-1	-2	-2	-3	-4	-4	-5	-6
	Ice Free		3	1	0	-1	-2	-2	-3	-3	-4	-5	-6	-6
Escorted Operations		Add +10												

Note: Adapted from IMO-Maritime Safety Committee, 94th session, “Technical Background to POLARIS” Retrieved May 10, 2016, from http://www.iacs.org.uk/document/public/Publications/Submissions_to_imo/pdf/consideration_and_adoption_of_amendments_to_mandatory_instruments_pdf2417.pdf

A table of Summer Risk Values (SRV) is arrived at by adjusting the WRV for some vessel classes and ice types in the summer season (Appendix 20). The SRV only applies if decayed ice is reported during the summer navigation season. Winter Risk values are applicable even in summer season if no decayed ice is reported (POLARIS, 2014) on the ice charts or by visual observations.

A Risk Index Outcome (RIO) in the POLARIS is derived similarly to the AIRSS Ice Numerals as follows:

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[49] RIO: Risk Index Outcome

$$RIO= (C_a*RV_a) + (C_b*RV_b) + (C_c*RV_c) +\ldots\ldots\ldots\ldots\ldots + (C_n*RV_n)$$

Where:

C_a = ice concentration in tenths of type ‘a.'

RV_a= risk value of ice type ‘a.'

C_n= ice concentration in tenths of type ‘n.'

RV_n= risk value of ice type ‘n.'

The POLARIS also gives out evaluation criteria for independent operations (Table 6) and icebreaker assisted operations (Table 7) and may serve as a good risk assessment tool for a Shipmaster both in the voyage planning stage as well as in ‘real time’[50]navigation during the course of the voyage.

Table 6

Criteria for Independent Operations

	Independent Operations	
RIO(ship)	Category (A & B)	Category-C
	PC1-PC7	PC below 7
RIO≥0	Operation Permitted	Operation Permitted
-10≤RIO<0	Limited Speed Operation Permitted	Not Permitted
RIO<-10	Not Permitted	Not Permitted

Note: Adapted from IMO-Maritime Safety Committee, 94th session, POLARIS – *proposed system for determining operational limitations in ice.* Retrieved from http://www.iacs.org.uk/document/public/Publications/Submissions_to_imo/pdf/consideration_and_adoption_of_amendments_to_mandatory_instruments_pdf2417.pdf

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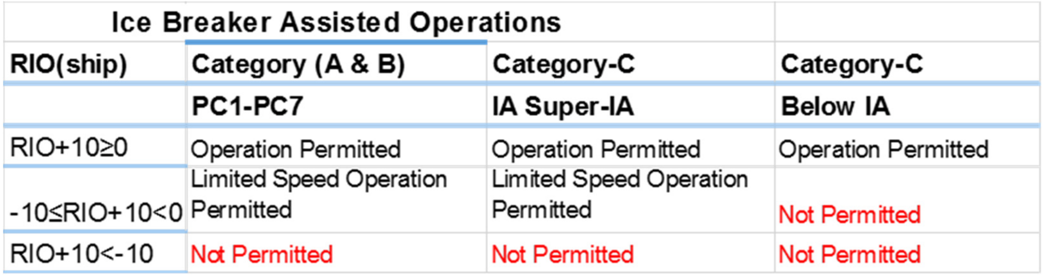
[50] ‘Real Time’: Actual bridge navigation

Table 7 *Criteria for Icebreaker assisted Operations*



Ice Breaker Assisted Operations			
RIO(ship)	**Category (A & B)**	**Category-C**	**Category-C**
	PC1-PC7	**IA Super-IA**	**Below IA**
RIO+10≥0	Operation Permitted	Operation Permitted	Operation Permitted
-10≤RIO+10<0	Limited Speed Operation Permitted	Limited Speed Operation Permitted	Not Permitted
RIO+10<-10	Not Permitted	Not Permitted	Not Permitted

Source: From IMO-Maritime Safety Committee, 94th session, POLARIS – *proposed system for determining operational limitations in ice.* Retrieved from *http://www.iacs.org.uk/document/public/Publications/Submissions_to_imo/pdf/consideration_and_adoption_of_amendments_to_mandatory_instruments_pdf2417.pdf*

This study has also used the POLARIS evaluation criteria (besides AIRSS) in the Route Optimization tool for decision-making in ice navigation. The POLARIS also gives out the thickness ranges of ice types between Thick First Year (TFI) and MYI, unlike the AIRSS. Calculation of average ice thickness is critical to the derivation of ship speed in various ice regimes that the author has utilized in the Route Optimization Model elucidated in this study. The Risk Index Outcome evaluation criteria stipulates marginal speed limitations for vessels of certain ice class should the RIO values satisfy the criteria -10≤ RIO < 0 for ships of certain ice categories (Table 8). The table indicates that a category ‘A’ ship (PC-3 to PC-5) is advised to proceed at a maximum speed of 5 knots if operating independently and should not exceed a speed of 5 knots when escorted by an icebreaker.

A category ‘C’(1ASuper-1A) vessel, on the other hand is not recommended to proceed independently in the same ice regime but may proceed at a maximum speed of 3 knots, if escorted.

Table 8

Marginal Capability Speed Limitations in Ice

Marginal Capability Speed Limitations		
Ship Category	Independent Ship Operation (knots)	Escorted Ship Operation (knots)
A(PC1-PC2)	NA	NA
A(PC3-PC5)	5	5
B(PC6-PC7)	3	3
C(IASuper-IA)	NA	3
C(Below IA)	NA	NA

Note: From IMO-Maritime Safety Committee, 94th session, POLARIS – *proposed system for determining operational limitations in ice.* Retrieved from *http://www.iacs.org.uk/document/public/Publications/Submissions_to_imo/pdf/consideration_and_adoption_of_amendments_to_mandatory_instruments_pdf2417.pdf*

The quantification of speed limitation in the POLARIS architecture acts as a useful risk assessment tool in decision making since speed is so critical to safe and efficient navigation in ice and particularly so in reduced visibility and during night navigation.

3.4 Prototype- Computer-Aided Route Optimization Model

The study has conceptualized a methodology of solving maritime transportation route problems in ArcGIS using the available data in the NWP. The model developed (Figure 6) is explicitly spatial and temporal in nature to facilitate its use in voyage planning and route optimization in ice. The model has utilized the existing concepts in the calculation of ice regime from the AIRSS methodology as well as the POLARIS concept wherever applicable. The proposed model is digital in scope and application and relies on a digital database of ice charts and electronic navigational charts. It does have shortcomings regarding the extent of ENC coverage and ice data quality currently experienced, but those areas will see a gradual improvement with advancing communication and satellite mapping technology by the middle of this century. Sea-ice would also have receded considerably as the ATAM projections allude to and the model will get better with evolving technology.

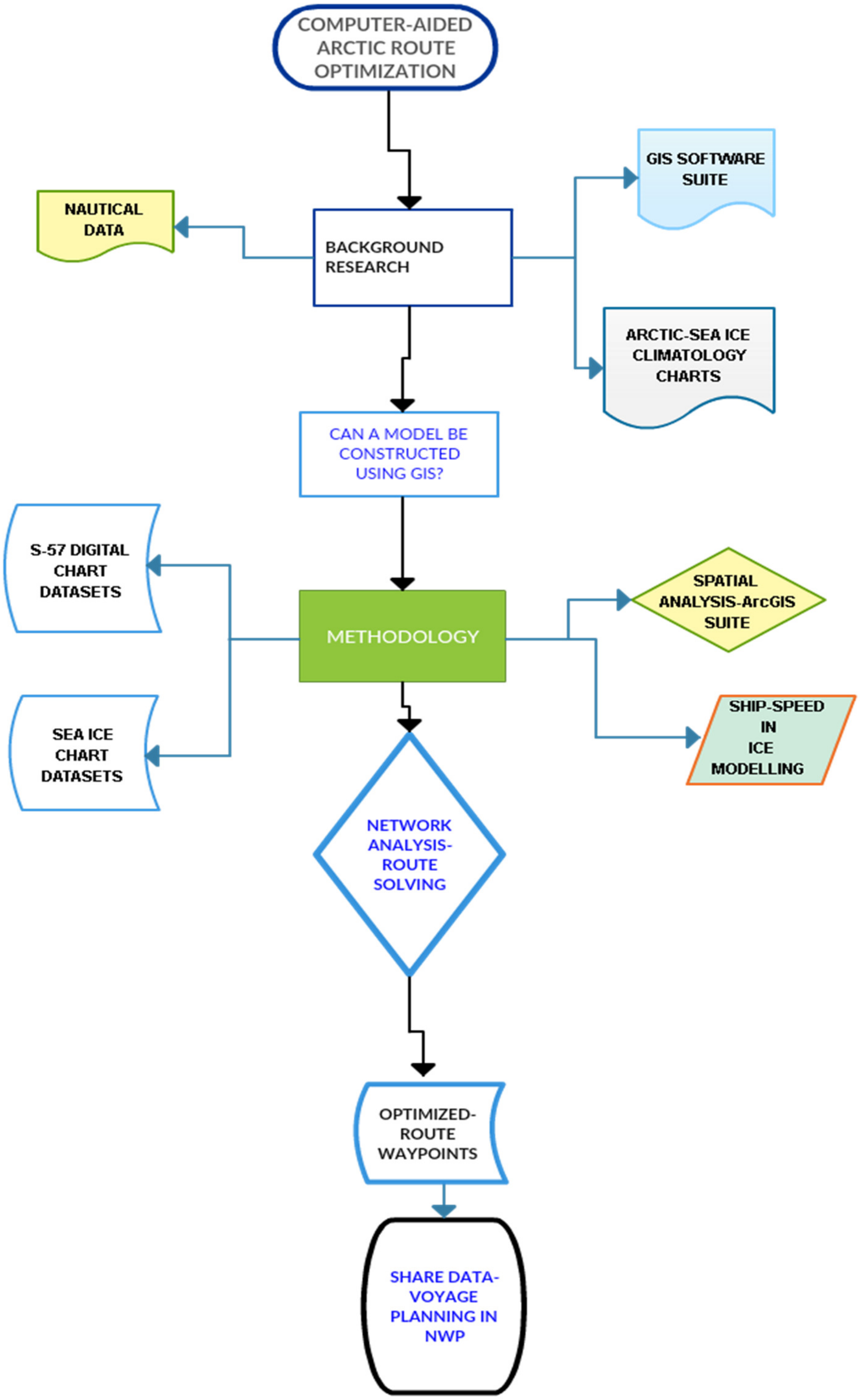


Figure 6: *Flow-Chart: Prototype Route Model (GIS)*

Source: Author

3.5 Maritime Routes: Network Modelling in GIS

The route optimization problem in ice navigation is essentially a spatial analysis problem that required an interdisciplinary solution in Geographic Information Systems (GIS). This study has integrated the world of Maritime Charting and GIS through MCDA to provide a solution to the route optimization problem. The GIS environment caters for spatial analysis on both Raster and Vector data sets. This study has performed the analysis in a Vector data environment that represents real world objects as Points, Lines or Polygons and stores information in 'Shapefiles' or a 'Geodatabase' (Kennedy, 2013). A 'File Geodatabase' (1TB) created for the purpose can store, query, and manage both spatial and non-spatial data, shared by several users simultaneously (ESRI, 2016). The goal is to share the optimized route output (waypoints) with the ship through ship-shore satellite communication or interfacing with existing navigation equipment such as the ECDIS.

The Model concept is structured as follows:

Goal: Evaluating a set of 3 identified sea routes in the Northwest Passage

Objectives: a) Route Safety and b) Route economy

Attributes:

Safety of the route would involve:

i. Navigational constraints with respect to ship size e.g. draft and charted depth of water
ii. Navigational hazards

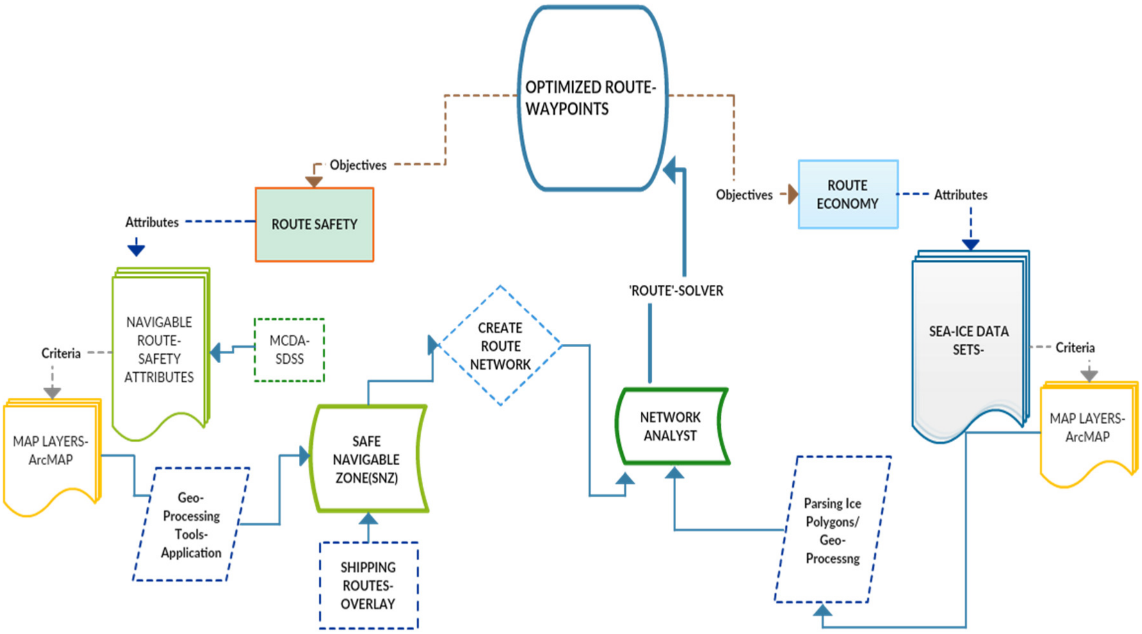
iii. Resistance provided by sea-ice
iv. Meteorological factors: Current, Wind and swell

Economic cost path would involve-

i. Length of passage- The longest route may not be the most expensive.
ii. Speed-in-ice: Sea-ice impedance will vary with ice concentration, stage of development, floe size
iii. Cost of fuel- assumed the same on all routes considering HFO/Diesel propulsion engines
iv. Depreciation/maintenance- Thicker ice navigation, heavier ice pressure –paint flaking, hull scrubbing, frame buckling, likelihood of cracks /general weakening of ship structure due to external loads.
v. Insurance premium- Depend on vessel age, Ice class type, Ship type
vi. Canal Fees/ Tariffs
vii. Crew wages and administration charges
viii. Capital cost of vessel.

The above involves three models namely, a) Route Optimization Model (CAROM), b) The Ship-Transit-in-ice Model and the Economic Cost Model. This study has not factored the current/wind/swell but has used only sea-ice data that was available. Criterion map layers are built in ArcMap based on the above. Geoprocessing is carried out in ArcGIS and the Network Analyst Extension is used to compute optimized routes.

ESRI's ArcGIS suite is the most convenient software among the various GI Systems available for reasons explained in section 2.6. The Canadian Ice Service and the NIC also use ArcGIS for producing ice analysis charts. The flowchart (Figure 7) displays route optimization process sequentially programmed in ArcGIS for spatial analysis and route solving. The three identified routes in the Northwest Passage are digitally scanned (geoprocessing) and tagged for charted depth soundings (≤ 20 meters) in the ArcMap that is deemed safe for most of the global container fleet, Post-Panamax[51] bulk carriers (WorldYards, 2016) and cruise ships comprising more than 80% of the global vessel fleet (Equasis, 2014) . This study conducts a validation process with the MV 'Nunavik' that made a voyage in September 2014 through the Northwest Passage to verify the CAROM derived optimized routes.



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[51] Post-Panamax: Denotes deep draft bulk carriers that did not fit the original Panama Canal lock gates.

Figure 7: *Route Optimization in Ice -ArcGIS*

Source: Author

The study has also compared and simulated scenarios with two ship types [52] and two different months of transit (summer season) besides a route validation with the MV 'Nunavik' to test the Route Optimization Model as mentioned above. The route optimization methodology as depicted in Figure 7 is explained in the following sections:

3.5.1 Safe Navigation Zone (SNZ)

The principal idea behind the 'SNZ' is the creation of a zone of safe water from the various S-57 ENC vector charts merged in the base layer. The base layer is created by selecting the relevant ENCs that the ship will use for passage planning in the NWP. A Spatial Decision Support System in the form of rule-based expert knowledge is applied to create an area of 'safe' water that incorporates all the charted dangers and cautionary areas where the ship must not venture and navigate at a safe distance with due regard to meteorological (wind, current etc.) and environmental variables (sea-ice, ice drift, ice pressure etc.) that can frequently change at sea. This study has modelled sea-ice resistance but other variables can be incorporated with data availability. Incidence of fog, reduced daylight and navigation in prolonged darkness in high latitudes may also be factored in the SDSS. The combined ice charts of the Eastern and Western Arctic will be overlain on the 'SNZ' layer and the 'Route' Solver applied in the Network Analyst. This process assimilates nautical data as available on the Electronic Navigation Charts and

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[52] Ship types: Polar class PC-4 and 1C

identifies all the dangers, cautionary areas and ‘rules of the road’[53] that ships must follow to conduct safe navigation. ‘Rules of the road’ refers to the International Regulations for Preventing Collisions at Sea (1972) and essentially defines the conduct of vessels at sea. The recognition given to Traffic Separation Schemes (TSS) is a case in point that gives guidance in determining safe speed, risk of collision and conduct of ships when operating near a TSS (Rule 10). The Route Model will include the TSS as a constraint if the same is charted. Currently, the NWP does not have a TSS hence it is not modelled.

The Mariner carries out a voyage planning before the start of a sea passage as stipulated under IMO guidelines (IMO, 2000) that include appraisal, planning, and execution and monitoring during the voyage. The underlying objective is to ensure the safety of navigation and protection of the marine environment, which, is the core philosophy of the IMO. A complete chapter on voyage planning and its functional requirements are included (chapter 11-3) in the draft Polar Code (IMO- Draft Polar Code, 2014) relevant in the context of this study. The demarcation of safe areas in relation to the ship’s draft and manoeuvring characteristics is essential to route plotting and voyage management, more so in the NWP where absence of hydrographic surveys, incomplete ENC coverage and lack of aids to navigation poses serious challenges that are well known and documented (Govt. of Canada-A, 2016). The S-57 Vector datasets contain multiple features aptly referred to as Geo-Object Classes (IHO object catalogue, 2000) and abbreviated as per the IHO nomenclature. Each chart contains hundreds of thousands of data points spatially separated but connected in a network of junctions and nodes. Computer-aided digital

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[53] Rules of the Road: International Regulations for Preventing Collisions at Sea (1972)

cartography is the fastest way of spatial analysis and decision support system currently available (Malczewski et al., 2015) for networks. ENCs of the NWP are used as the base layer for spatial analysis (vector charts) in ESRI's ArcGIS suite. The relevant set of S-57 Electronic Navigation Charts is merged to create a single base layer; before allocating a datum and projection to the map. Defining the projection for a dataset is a very important part of working in ArcGIS because every dataset has a coordinate system, which is used to integrate it with other geographic data layers within a common coordinate framework such as a map. Coordinate systems enable users to integrate datasets within maps as well as to perform various integrated analytical operations such as overlaying data layers from disparate sources and other coordinate systems. The geographic coordinate system and projected coordinate system of the ENCs as loaded in the ArcMap is found to be 'WGS 84' and 'World Mercator' respectively. To overlay and integrate the sea-ice data, the projected coordinate systems of both the data layers must match. The original projection system of the CIS datasets for example is Lambert Conformal. It is converted to a Mercator projection after the sea-ice datasets are loaded in the ArcMap to prevent any conflict sing a geoprocessing tool. A 'File Geodatabase' is created in 'ArcCatalog'[54] and the map saved in 'ArcMap' for spatial analysis. A spatial query is performed to identify all charted depth data points less than 20-meter depth (depth ≤20 meter) and tagged. The identified data points are also marked with a guard zone/buffer based on the user's safety preferences. The list of geo object classes (Table 9) identified may increase as per depth of information contained in the charts. The buffer limits can be easily adjusted as per the user's preference, a distinct advantage of modelling. The navigational constraints and the

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[54] ArcCatalog: Interface to manage Geodatabase in ArcGIS

geo object classes selected have been arrived at from author's experience as well as discussions with several Ice Pilots and Icebreaker Captains having expertise in Arctic navigation.

Table 9
Geo Object Classes and Buffers for 'SNZ.'

	Geo-Object Class	Buffer
SN		NM
1	Coast Line & Islands	2
2	Charted Depth Soundings≤20 M	0.1
3	Obstruction Areas	1
4	Obstruction Points	1
5	Wreck	1
6	Un-surveyed Areas	0.1

Source: Author

Based upon the ship's draft a judicious balance between route safety and route economy is essential. The list may get longer on charts that have more geo-object classes identified as safety parameters e.g. North Sea charts with oil exploration activities. The 'SNZ' layer incorporates all the limitations imposed (Figure 8), and the navigable area polygon is much smaller than the charted sea-area for the specific vessel under consideration. Large buffer values may increase safety at the cost of limiting the navigable area without any tangible benefits. The meta-object class 'Coverage' in ArcMap represents the entire sea area of the NWP. To achieve the 'SNZ' layer, the buffered area for each object class is algebraically subtracted from the 'Sea Area' polygon (Coverage) in a sequential manner as under:

(‘SNZ’) Layer = (Coverage)-(Landarea_buffer) - (ObstructionP_buffer) - (ObstructionA_buffer) - (Wrecks_buffer) - (Unsurveyed-areas_buffer) - (Soundings ≤20meter_buffer). The ‘Erase’ geoprocessing tool is used in successive steps to arrive at the final ‘SNZ’ layer. A schematic representation of the process is illustrated:

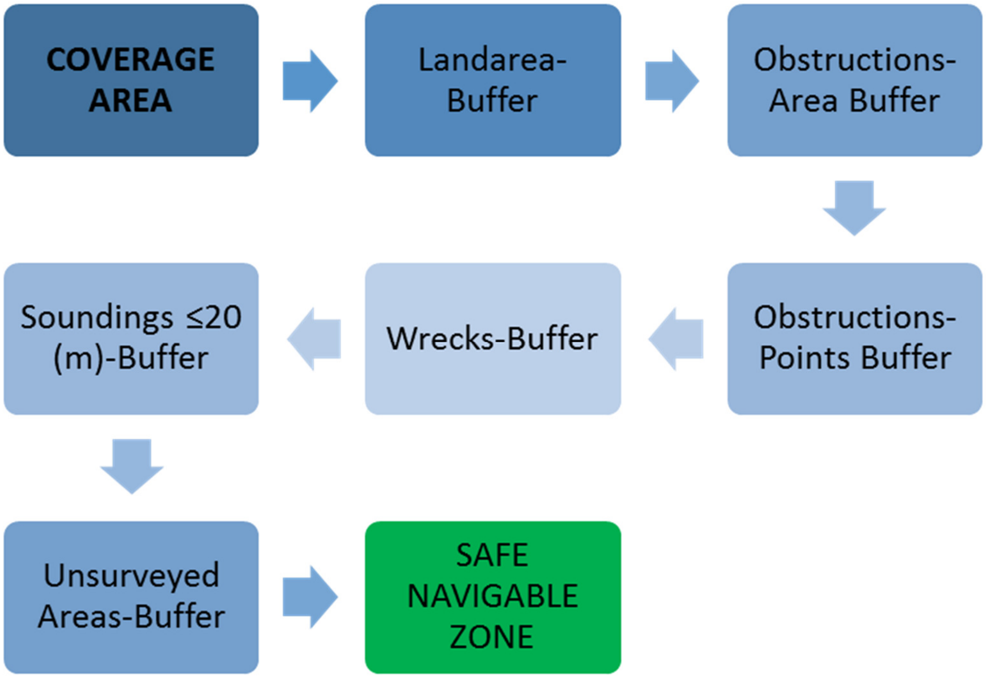

Figure 8: *Schematic diagram –Safe Navigation Zone (SNZ)*

Source: Author

The three shipping routes as plotted on the paper charts are subsequently overlaid on the ‘SNZ’ layer after the requisite horizontal datum allocation and map projection settings as explained earlier in this section.

3.5.2 Voyage Planning-Northwest Passage

Voyage planning is an integral part of the vessel sailing plan and is executed from berth to berth (port of departure to the arrival port) in two phases namely a) the strategic phase while in open waters and b) the tactical phase during navigation in ice. IMO has put out guidelines (IMO, 2000) for the same and this forms a part of safety checklist during the ISM Code compliance audits[55]. The 'monitoring' and 'execution' aspect ensures that the routes as planned may change along the way, should the conditions related to safety change. Voyage planning took an added safety dimension in the Arctic waters as referred to in the IMO Polar Code (chapter 2) with the introduction of the Polar Water Operational Manual (PWOM) and recognized as a critical risk mitigation tool for Polar Navigation (American Bureau of Shipping, 2016).

This study has conducted a voyage plan between two geo-referenced points, the 'origin' being a point in Lancaster Sound (74° N,80° W), the 'destination' a point west of Banks Island (71.5°N, 128.566°W) on the nautical paper charts of the area and plotted three separate routes between the 'origin' and 'destination' (Appendix 21). The waypoints for all the routes plotted on the paper charts are subsequently transferred to the 'SNZ' layer in ArcGIS obtained in the previous section. The 'Safe Navigation Zone' layer acts as a base layer upon which the three routes are overlain from the waypoints obtained previously. The voyage planning and the subsequent route plotting is done for open water navigation (strategic) at this stage without considering any other environment variables such as current, wind and sea-ice. The route optimization algorithm is appropriately set

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[55] Audits: Carried out annually by approved surveyors

up to provide a solution once the route network is properly set up and defined in the 'Network Analyst.' Inadequate surveying and electronic chart coverage in the Canadian Arctic (Govt. of Canada-A, 2016) lead this study to merge S-57 ENCs and nautical paper charts with geoprocessing techniques to design a workable digital route network in the Northwest Passage. The study notes the entire area in the Dolphin and Union Straits and western parts of the Coronation Gulf is largely not surveyed (Figure 9), the only passage for ships transiting in and out of the Amundsen Gulf.

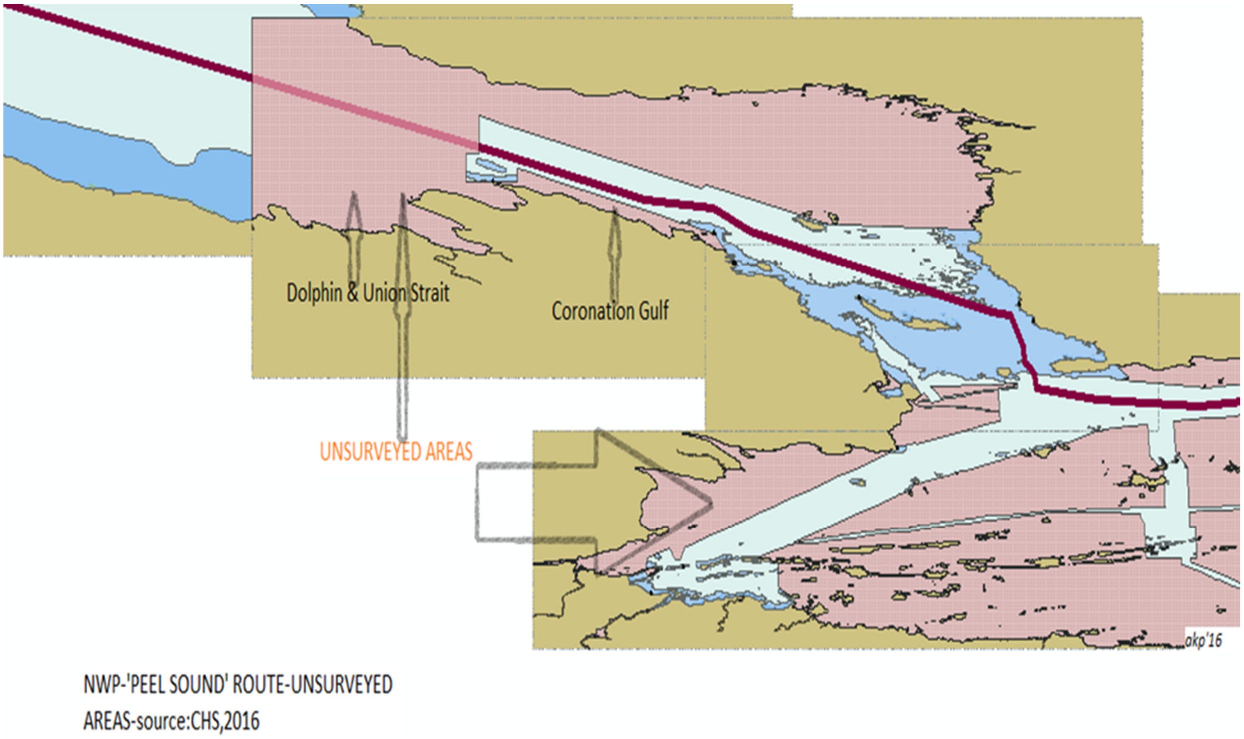

Figure 9: *Unsurveyed Areas-Peel Sound Route*

Source: Adapted from CHS charts

The Peel Sound passage is by far the most popular route (Figure 10) for destination traffic and resupply ships in the Canadian Arctic (Northwest Territories, 2015) with Coronation Gulf at the western end.

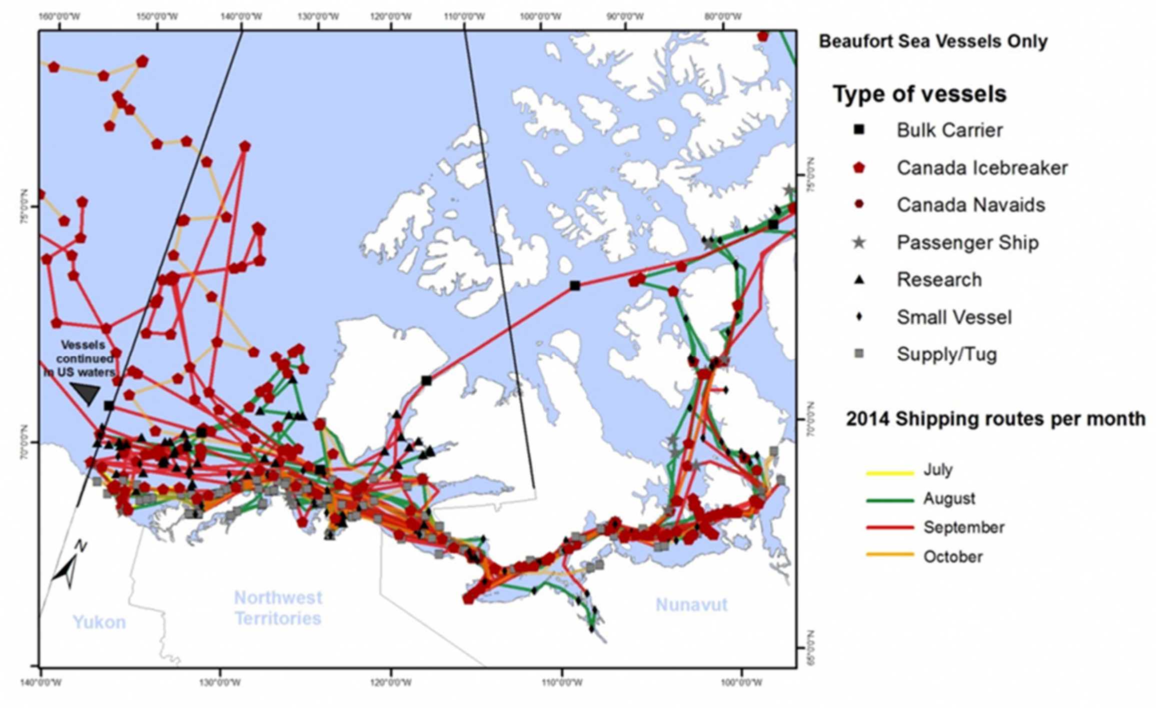

Figure 10: *NORDREG Shipping Traffic Data (2014)*

Source: **(Northwest Territories, 2015)**. Retrieved May 10, 2016, from http://www.enr.gov.nt.ca/state-environment/73-trends-shipping-northwest-passage-and-beaufort-sea.

The shipping routes plotted on the S-57 ENC base layer pass through shallow water areas and narrow passages in parts of Victoria Strait, Coronation Gulf, and the Prince of Wales Strait. The western portion of the Parry Channel stretching from Viscount Melville Sound to the M’Clure Strait does not have S-57 ENC coverage, and neither do the southern part of Prince of Wales Strait and the northern part of the Peel Sound channel. Safety buffers of varying magnitudes are established along all the three routes wherever necessary to complete the network with the existing electronic navigation charts. The 'Union' geoprocessing tool that preserves the attributes and features of all layers in the output is employed to join the additional features thereby creating the final 'SNZ' layer with the route layer overlain. The 'Union' function ensures that all information is preserved in the output.

3.5.3 Random Route Network

A route network is required between the 'origin' and 'destination' to provide the 'Route' Solver a choice of multiple nodes and junctions to compute the best route (optimized) solution. Random data points resembling a mesh is generated with the help of geoprocessing tools enables creation of the maritime network to traverse between the 'origin' and 'destination.' The random route network for a portion of the Peel Sound Route is depicted (Figure 11) here:

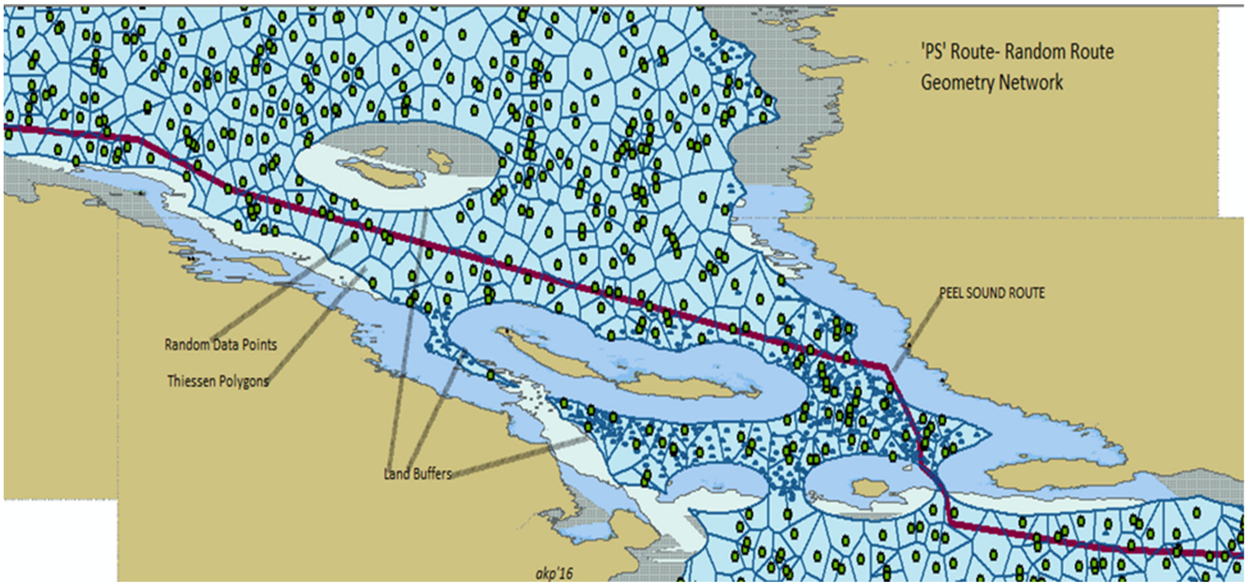

Figure 11: *Random Route Geometry Network (GIS)-Peel Sound Route*

Source: GIS mapping -Author

The shallow areas and buffer zones around the outlying islands can also be seen. This research has attempted route simulations generating random data points in the network. All the data points are triangulated into a triangulated irregular network (TIN) that meets the Delaunay criterion. The perpendicular bisectors for each triangle edge are generated, forming the edges of a Thiessen Polygon.

The study conducted Route Modelling between 10^5 to $7*10^5$ proximal polygons, the density of the route network limited only by the computer processing power. Thiessen Polygons are used for mathematical analysis in network modules. The polygon boundaries define the area closest to each point about all other points. The lower data point option (10^5 polygons) is favoured for the intended purpose after multiple iterations in a restricted space such as the 'NWP-SNZ'[56] to maintain a trade-off between computer processing speed and route network density. The next step is the introduction of a 'Feature Dataset' in the 'File Geodatabase' to integrate the related feature classes[57] spatially and thematically with the objective of building a 'Network Dataset' and bring in the environment variables such as sea-ice data to integrate with the existing feature classes. This is done through a sequence of commands in the Network Analyst. The 'ArcCatalog' tree is thus arranged (Figure 12) with all the 'Feature classes' under one 'Feature Dataset' having the same projected coordinate (World Mercator) that had been set up earlier. The shipping route 'Network Dataset' also requires establishing

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[56] NWP-SNZ: Northwest Passage-Safe Navigation Zone

[57] Feature Class: A homogenous collection of common features-points, lines and polygons to represent real world objects on Vector charts having same spatial representation and common attributes.

connectivity and assigning values to defined attributes besides creating the network elements. A prerequisite of the 'Network Dataset' is the extraction of the 'Feature Class' ('SNZ') into the 'Feature Dataset' for the subsequent network assembly to be accomplished.

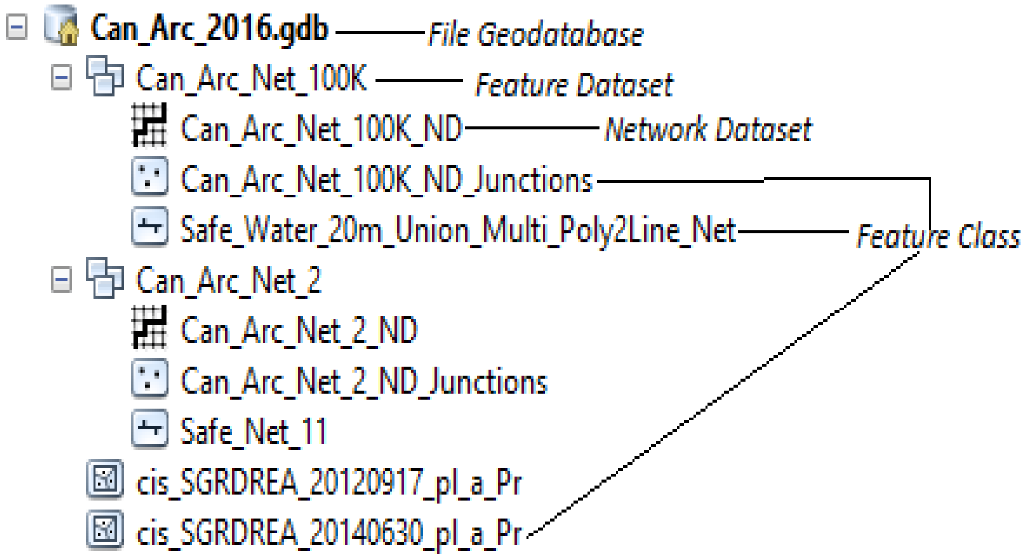


Figure 12*: Arc Catalog Tree- Network Dataset*

Source: Author

A simple maritime transport network dataset is created using the 'Network Dataset' wizard as illustrated above; the connectivity tested for continuity and validity. Environmental variables can now be loaded into the network. The network can model any other environmental /meteorological variable that influences a maritime route network in ice namely, ice pressure, ice drift, current and wind data among others, although this study has dealt with the sea ice environmental variable only.

3.5.4 Analysis –Ice Charts

Sea ice is the only environment variable that distinguishes Arctic navigation from open water ocean passages. A ship deals with the rest of the weather elements that affect the speed (swell, the wind, current and fog) and safe passage as a standard sailing routine in any part of the world, hence the navigational risk management in ice takes a stellar dimension. Information about ice thus becomes indispensable in the Arctic in general and more so in the NWP that will encounter tougher ice climatology than the rest of the Arctic as forecasted (Smith and Stephenson, 2013). A multitude of data sources including satellite and aerial reconnaissance (drones, helicopters, aircraft) and ship-sourced observations are increasingly becoming available that contain high-resolution digital imagery and better ice forecasts. This study has used sea-ice climatology data available on the CIS charts in the SIGRID-3 format. The spatial coverage of the CIS data includes both the Eastern and Western Arctic that covers the entire NWP, the focus area of this study. The temporal resolution for the Northern Canadian waters is weekly (summer), and bi-weekly (winter), and the digital charts are ArcGIS compatible (NSIDC-D, 2016). Sea-ice data from the year 2014 for select dates from the months of June and September is utilized in modelling two scenarios with two ship types (Category 'A' and 'C') to conduct route analysis and optimized route prediction while navigating independently in ice. Ice datasets from 29th September'14 are used for the September modelling (Scenario-2) with the vessel MV 'Nunavik,' a Category 'A' (PC4 class) ship. The other ship used in the study is the MV 'Berge Atlantic', a Polar Category 'C' vessel. The SIGRID-3 Vector datasets map the ice fields as polygons that include ice climatology parameters contained in the attribute data tables. Three hundred seventy-five (375) ice polygons were analysed from the September ice dataset by segregating them into eight categories based on the total ice concentration (CT) numbers. The Partial Ice Concentration (CA, CB, and CC) and the Stage of Development (SA, SB, and SC) data for each of the categories are subsequently analysed. The average ice thickness for each partial concentration category is thereby calculated from the CIS datasets. The average ice thickness per ice regime category is thus, utilized to compute the Ice Numeral from the AIRSS 'Ice Multiplier' table. The Risk Index Outcome (RIO) as proposed by the POLARIS methodology closely resembles the AIRSS concept, and the RIO values are also calculated simultaneously to compare the two (Table 10) methods.

Table 10

Computation of Ice Numerals/Ice thickness

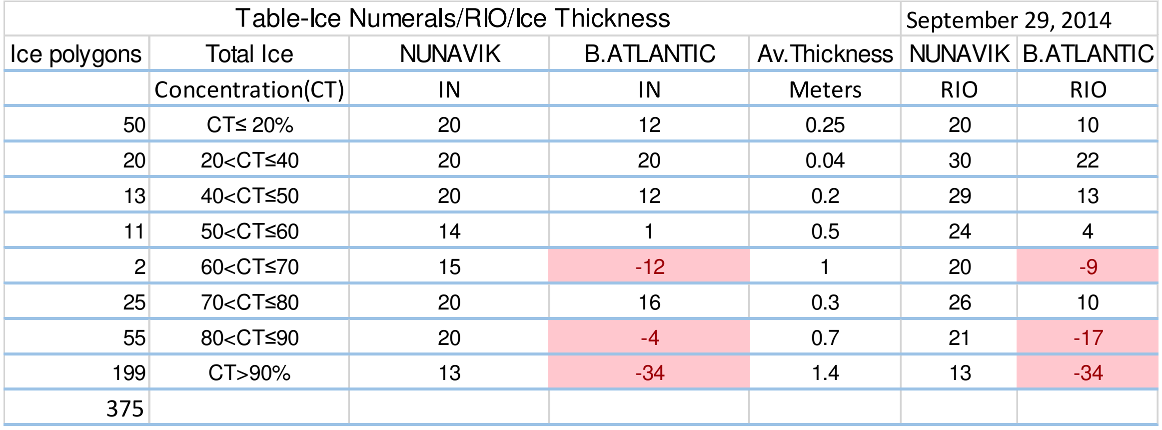


Table-Ice Numerals/RIO/Ice Thickness					September 29, 2014	
Ice polygons	Total Ice	NUNAVIK	B.ATLANTIC	Av.Thickness	NUNAVIK	B.ATLANTIC
	Concentration(CT)	IN	IN	Meters	RIO	RIO
50	CT≤ 20%	20	12	0.25	20	10
20	20<CT≤40	20	20	0.04	30	22
13	40<CT≤50	20	12	0.2	29	13
11	50<CT≤60	14	1	0.5	24	4
2	60<CT≤70	15	-12	1	20	-9
25	70<CT≤80	20	16	0.3	26	10
55	80<CT≤90	20	-4	0.7	21	-17
199	CT>90%	13	-34	1.4	13	-34
375						

Note: Adapted from CIS ice datasets September 29, 2014. Numbers in red indicate areas not recommended for navigation without icebreaker escort.

The above table may act as an important voyage-planning tool for the Shipmaster/ice-navigator as the data is acquired before the vessel enters the ice edge and at every chart update during the voyage, if available. The negative numbers in the table indicate areas where the vessel may not proceed without an icebreaker escort as per AIRSS guidelines, an excellent planning tool for the shipboard management to notify the relevant authorities and prepare for the contingency well in advance. The ice attribute table also contains predicted ice thickness per ice concentration (CT) category that is made use of in the ship Ship-Transit Model for computing the net resistive force offered by sea-ice to a ship in motion.

3.5.5 Ship Transit-In-Ice Model

Various quantitative models have been put forward to predict ship resistance in level ice that includes both empirical and numerical (Valanto, 2009) derivations. While both approaches have their strength and weaknesses, Gustav Lindqvist (1989) presented a semi-empirical model of calculating ship resistance that is representative of standard methods without resorting to full-scale model tests. Riska, Wilhelmson, Englund and Leiviska, (1997) presented a modified version of the Lindqvist methodology assuming level ice resistance (R_i) to be linear with speed (v) where:

$$R_i = C_1 + C_2 * v \tag{1}$$

C_1 and C_2 being constant terms represented by the equation:

$$C_1 = f_1 \times \frac{1}{2 \times \frac{T}{B} + 1} \times B \times L_{par} \times h_i + (1 + 0.021\varphi)(f_2 \times B \times h_{i^2} + f_3 \times L_{bow} \times h_{i^2} + f_4 \times B \times L_{bow} \times h_i) \tag{2}$$

$$C_2 = (1 + 0.063\varphi)(g_1 \times h_{i^{1.5}} + g_2 \times B \times h_i) + g_3 \times h_i \left(1 + 1.2 \times \frac{T}{B}\right) \times \frac{B^2}{\sqrt{L}} \tag{3}$$

The values of the constants f_1, f_2, f_3, f_4 and g_1, g_2, g_3 and the symbol nomenclature used in the formulae are as described (Appendix 22).

A distinct advantage of using the Riska method is that the rest of the parameters required to solve the terms C_1 and C_2 are known from the ship data calculations (Table 11).

Having calculated the resistance in level ice (R_i), it is imperative to determine the net thrust available (T_{net}) to the ship in ice regimes of various thicknesses. Riska et al., (1997) calculated the net thrust and the bollard pull using the formula:

$$T_{net}(V)=\left(1-\frac{1}{3}\times\frac{v}{v_{ow}}\ -\frac{2}{3}\left(\frac{v}{v_{ow}}\right)^{2}\ \right)\times T_{pull} \quad (4),$$

$$T_{pull}=K_e\left(P_5\times D_p\right)^{\frac{2}{3}} \quad (5)$$

$$T_{NET}\left(v_{level\ ice}\right)=R_i \quad (6)$$

The net thrust would be the algebraic difference of the available power (4) in that ice regime and the level ice resistance calculated in (1) assuming the resistance is linear with speed. A vessel performance table is thus, computed by plugging the ship's parameters in the formula for incremental speeds and incremental ice thicknesses (Kotovirta et al., 2008). The table shows that a ship would exhaust (equation 6) all its available engine power to move ahead in the ice of certain thickness beyond a certain speed as calculated by the formula. Performance tables thus constructed for both the Category 'A' and Category 'C' ship that used in the models. The extent of ice concentration also varies in ice regimes affecting the ship's speed. The ship performance table is devised (Kotovirta et al., 2008) for speed between ice concentrations ranging from 5/10th to 10/10th ice coverage as per equation (7). The average ice thickness calculated from the ice chart datasets corresponding to the ice regimes as categorized provides the input to calculate the speed ($V_{\text{level ice}}$) in equation (6) that solves equation (9). Open water speed (v_{ow}) is assumed in ice concentrations ranging from 5/10th or less coverage (8) and is widely borne out of Shipmaster / Ice Pilot's experience in ice-infested waters. A safe speed has more to do with a safe speed of operation considering visibility, operations in darkness and likelihood of icebergs/growlers in the area. The speed estimates may vary with the length of operator's experience in ice and ship manoeuvring characteristics. The speed estimation (v_{ow}) for ice concentration (CT≤ 50%) in the Ship-Transit Model is based on the author’s experience in ice infested waters with due regard to the likelihood of icebergs /growlers encountered in open waters, reduced visibility due to fog and operations in darkness.

$$\tilde{\upsilon} = \begin{cases} \frac{(C90-C)*v_{ow}+(C-C60)*V_{Level\ Ice}}{(C90-C60)} : C60 < C < C90 \end{cases} \tag{7}$$

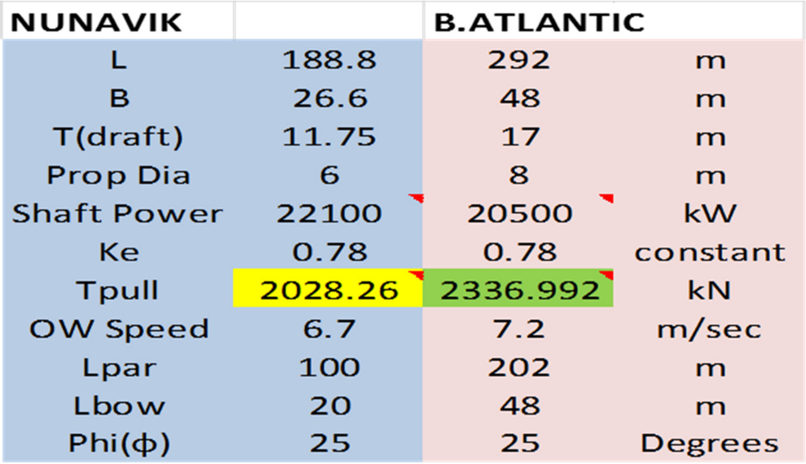
$$v_{ow}: C \leq C60 \tag{8}$$

$$V/_{level\ Ice} = C \geq C90 \tag{9}$$

The speed calculated in the ship performance table is eventually used in the ‘Network Dataset’ built to model ice impedance as a function of the ship’s estimated speed in ice through the variable ice regimes.

Table 11

Ship Data: Resistance In-Ice Calculations



NUNAVIK		B.ATLANTIC	
L	188.8	292	m
B	26.6	48	m
T(draft)	11.75	17	m
Prop Dia	6	8	m
Shaft Power	22100	20500	kW
Ke	0.78	0.78	constant
Tpull	2028.26	2336.992	kN
OW Speed	6.7	7.2	m/sec
Lpar	100	202	m
Lbow	20	48	m
Phi(ϕ)	25	25	Degrees

Note: Calculations from Ship Parameters-Author

3.6 Electronic Navigation Charts-Interface with ArcGIS

The digital route model as conceived has combined elements of cartography, ENCs, sea-ice charts (vector) and integrated in them using Geographic Information Systems (GIS). The Canadian Hydrographic Survey publishes the Electronic Navigation Charts (.000) on CD's for the Arctic in the volume 'Nor-A' and is available with distributing agents throughout the world. The ENC coverage of the Canadian Arctic is still incomplete as mentioned earlier and CHS nautical paper charts used in the route plotting to build the route network after digitization. A schematic view of the interface process between Electronic Navigation Charts and nautical paper charts in ArcGIS (Figure 13) follows:

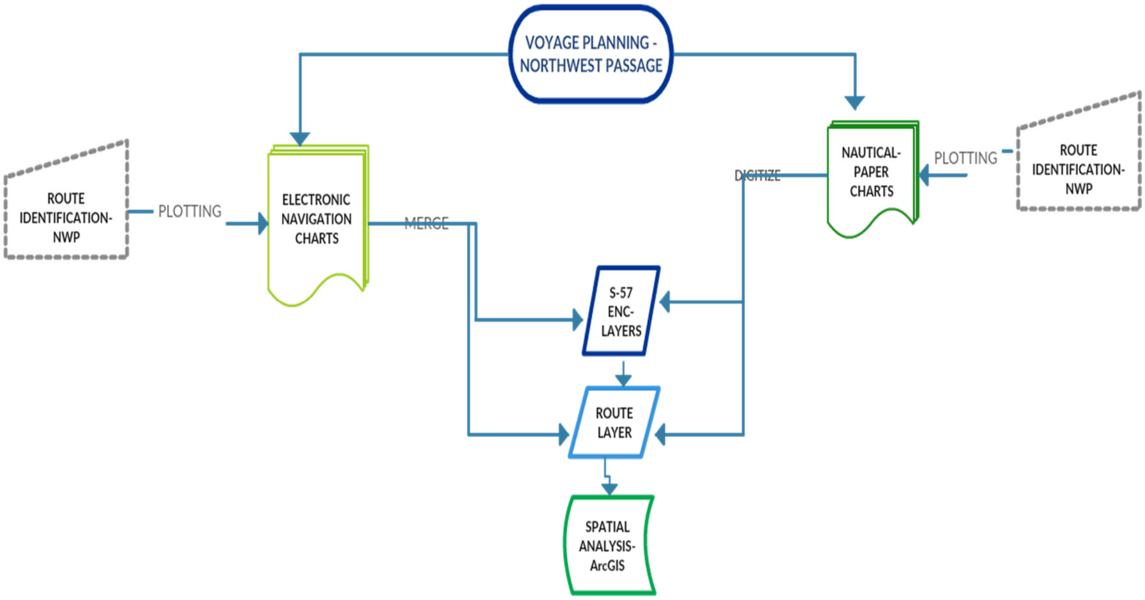


Figure 13: *Schematic View-Voyage Planning in ArcGIS*

Source: Author

Electronic Navigation Charts like their paper-based counterparts are produced in different scales depending on the areas they portray. Charts of ocean areas, for instance, are in small scale (large area coverage) whereas; the coastal and harbour charts have greater detail ascribed to them (large-scale charts). The Northwest Passage comprises of multiple charts of different scales, and a complete route mapping requires merging separate charts to create a common base layer. A common cartographic projection and the appropriate coordinate system are allocated to all the map layers' prior analysis in ArcGIS. IHO has specified an Object catalogue (Appendix 23), a data schema for the S-57 transfer protocol, the primary function being to provide a means of depicting real world entities (lighthouses, beacons, buoys, wrecks, etc.) on the charts. These entity types are referred to as feature object classes and ascribed attributes; called meta-data. The horizontal datum is set to WGS-84[58], positions referred to in decimals of latitude and longitude, heights and depths set in meters (IHO object catalogue S-57, Appendix-A and Appendix-B). A navigable area of water safe enough for the vessel size is eventually achieved after spatial analysis incorporating all the safety buffers into account. CIS initiated sea ice charts in conjunction with Multi-criteria Decision Analysis is utilized to arrive at an 'SNZ' layer that serves as the principal foundation layer for network building and eventual route optimization. No other environment variables that affect ship speed is considered in the route modelling. The author has utilized his experience as well as inputs from several Ice Pilots and Ice-breaker captains to set up the parameters for the navigational constraints termed 'buffers' in the model. It is possible to adjust the buffer values based upon the draft and manoeuvring characteristics of the vessel and user preferences. A reasonable

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[58] WGS-84: Reference coordinate system used by GPS; established in 1984, revised 2004.

balance between route safety and route economy is thereby, achieved through the creation of the ‘SNZ’ layer.

3.7 Random Route Geometry-NWP

The ‘route’-solving algorithm in the model solves the least cost path between a fixed ‘origin’ and ‘destination’ along the ‘SNZ’ determined earlier by MCDA-SDSS techniques. The route that the vessel would take between the two points involves a multi-path network within the confines of the ‘SNZ.' The network consists of multiple nodes and junctions resembling polygons that the vessel may traverse to get an optimized routeing solution with the ice chart overlain. This study has conducted simulations within a range of 10^5 to $7*10^5$ random points to generate random route geometry in the NWP. The accuracy does increase with polygon density but gets impractical for navigation due to the sheer number of vertices (waypoints) in a very confined area beside a marked slowdown in computer graphics display performance.

3.8 Network Analysis with Hierarchy

The Route Optimization model uses the ‘Route’ Solver with a hierarchical route network dataset created within the ArcGIS Network Analyst extension. The ‘origin’ and ‘destination’ coordinates can be reversed for the model to travel in either direction between two fixed points along a random network of polygons (nodes and junctions) generated for this purpose. The ‘Route’ Solver in ArcGIS conforms to the well-known Dijkstra algorithm to solve shortest path route problems (ESRI, 2016). A hierarchical network created to model ice impedance as a function of the ship’s estimated speed in ice through the variable ice regimes. The ratio of open water speed to the calculated speed in ice is termed ‘scaled cost’ within ‘Network Analyst.' The degree of difficulty to negotiate a certain ice regime is inversely proportional to the ‘scaled cost.' The ship clocks a higher speed in sea-ice with reducing ‘scaled cost’ and higher positive Ice Numerals. A zero speed or negative Ice Numerals are allocated ‘restriction’ in the ‘Network Analyst’ to enable the ‘Route’ solver avoid such areas and find a route of least resistance through sea-ice. The ‘restrictions’ readily changed to ‘scaled costs’ if the ice regime becomes a positive numeral area in a subsequent ice prediction.

3.9 Route Optimization (computer based)-NWP

The ‘Route’ Solver in the Network Analyst is a distance analysis tool within ArcGIS that can calculate the most cost-effective route between a source and destination. The solver generates a series of intermediate vertices along the route, that are used as waypoints along the intended track after suitable smoothening (simplification) to make it useful for efficient navigation in ice. Ice impedance programmed as a time-based attribute in the network is a ratio of the ship’s speed in open water to the estimated speed in the ice of a tabulated ice concentration as noted earlier. The speed table (Appendix 24) is ship specific, and a function of the engine power and the total resistance offered in the level ice that may change with the ice regime. This study has categorized ice concentration into 7 or 8 separate categories (depending on ice polygons) based upon the percentage coverage and calculated the estimated speed in each category to determine the ‘scaled cost’ of the barrier imposed by ice. Since the time of transit depends on the magnitude of impedance through each category of ice, the optimized routeing solution is akin to practical navigation in ice. Furthermore, using hierarchy in a network analysis makes use of a heuristic that reduces the computation time by limiting the search mostly to the higher levels of the hierarchy ((ESRI, 2016).

3.10 Verification and Validation

The Network Analyst extension uses Dijkstra's algorithm to determine the shortest path between two fixed georeferenced positions in the ArcGIS suite. In the absence of a full-scale verification on board a ship, the study has created the under mentioned methods to verify and validate the Route Model:

I. Transit Case Study: Build 2 scenarios (Scenario 1 and 2) based upon season of transit with two types of vessels (Category 'A' and 'C') as defined in the draft Polar Code.
II. 'Nunavik' Route Validation: Create a model to map the voyage of the MV 'Nunavik' through the NWP with the ice datasets from 29 September 2014.
III. Route Simulation: Apply simulation techniques to remove or add barriers or incrementally change impedance factors and analyse predicted outcomes.

A Category 'A' ship is "*designed to operate in Polar waters in at least medium first-year ice which may include old ice inclusion*" (IMO- Draft Polar Code, 2014). The draft Polar Code defines a Category 'C' ship as one "*designed to operate in open water or in ice conditions less severe than those included in Category 'A' or 'B.'*" For the Polar Code, Open Water "*means a large area of freely navigable water in which sea ice is present in* *concentrations less than 1/10."* The underlying reason for selecting the two categories of ships is a) ship data for both ship types was readily available; b) The two classes ('A' and 'C') represent two extremities of ice classification and sea-ice extent for calculation of Ice Numerals. Months of transit (June and September) represent the beginning and peak of summer navigation season in the NWP.

Table 12
CAROM Validation methods

CAROM- VALIDATION METHODS					
Route validation		MV 'Nunavik'	NWP-Voyage	23/09/2014	28/09/2014
		Category/ Class/Month		Transit	
Transit Case Study		A	C	Year	Date
	Scenarios	PC4	1C		
	1	June	June	2014	30/06/2014
	2	September	September	2014	29/09/2014
			NWP Voyage	Route	Date
Route simulation		MV 'Nunavik'	June	POWS	30/06/2014
		MV'Berge Atlantic	September	M'Clure Strait	29/09/2014
			September	Peel Sound	29/09/2014

Source: Author.

The two scenarios for the Transit Case Study (Table 12) is developed as follows: Analysis of CIS ice data for the months of June and September to calculate the Ice Numerals for the ice regimes as explain in section 2.4.4.1. The SIGRID-3 datasets will also be analyzed to determine the average thickness of ice in each ice concentration (CT) category to calculate the resistance in ice (R_i) and eventually the estimated speed.

The ice class (PC4) cargo vessel MV "Nunavik" made a westbound voyage through the NWP in September 2014. This study has reconstructed the voyage in the Model for validation purposes with route data available on FEDNAV's[59] website. Although the ice charts were not obtainable for the exact days of the passage, the ice chart for September 29, 2014 was used instead. The vessel had transited the NWP between 23 September and 28 September 2014 (Nunavik Logbook, 2014) and a comparative route validation modelled to verify the 'Nunavik' route with the CAROM.

A simulation study will also be conducted as a third method of verifying the CAROM by simulating additional barriers incrementally and test all the three routes in the NWP. The ice datasets will be the same used in the Transit Case Study.

3.11 Economic Viability: Cost-Benefit Route Model

For ocean transport solutions, a common measure of performance is the 'Required Freight Rate' (Stopford, 1997). Actual shipping rates depend on supply and demand, and can be above or below the 'Required Freight Rate.' Shipping rates also reflect the commodity being carried i.e. value of goods (high value finished goods vs. low-value raw goods). The 'RFR' is a function of the following variables about the container ship under study:

I. Annual cargo capacity of the ship via Northwest Passage/Panama Canal
    a. Number of round-trips/year
        - Speed
        - Distance
        - Port turnaround time
        - Canal waiting time
        - Downtime for maintenance/year

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[59] FEDNAV: Canadian Shipping company, owner of the MV 'Nunavik'

    b. Ship's capacity/tonnage

II. Operating cost

III. Capital recovery of vessel

The theoretical round trips/year is first calculated assuming the following:

- Ship capacity utilization
- No port delays assumed.
- No downtime due to lack of demand or extreme weather/beset in ice is considered.
- Sailing productivity factor –assumed 93% as per the industry norms.

The 'RFR' thus calculated is exclusive of port charges and customs duties.

In the current freight rate scenario, freight rates are extremely low, as the 'Neo Panamax'[60] container ships have flooded the market with not enough cargo to ship around the world. The shipping rates as witnessed in the Shanghai Containerized Freight Index (Figure 14) prove that no ocean carrier will be able to return cost of capital at these rates irrespective of the shipping route.

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[60] Neo Panamax: Container ships up to 49-meter beam that can carry more than 10000 TEUs through the expanded Panama Canal locks.

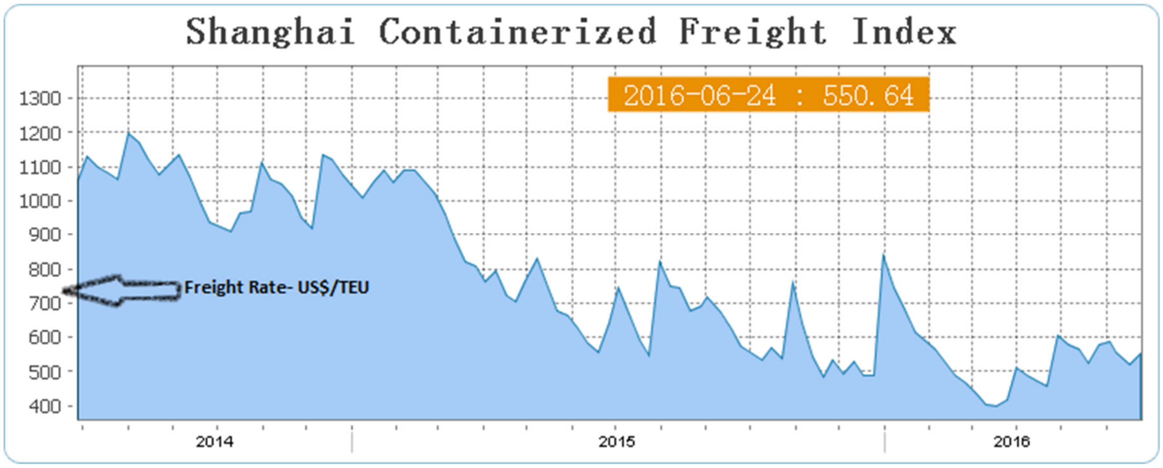


Figure 14: *Shanghai Container Freight Index*

Source: Adapted from Shanghai Shipping Exchange (2016). Retrieved June 27, 2016, from http://www1.chineseshipping.com.cn/en/indices/scfinew.jsp

3.12 Summary- Research Methodology

Creation of the 'Safe Navigation Zone' by applying MCDA techniques is the building block of the Computer-aided Arctic Route Model (CAROM). The application of Spatial Decision Support System (SDSS) in the maritime domain requires navigational expertise in ice to allocate attributes to the several criteria contributing to the MCDA. The 'SNZ' acts as the bedrock of support for the subsequent random route geometry, ice chart overlay and the eventual route optimization process conceived in the study. The three models discussed in this chapter should collectively give us an answer to the economic viability of the NWP as a viable trans-Arctic route alternative to the Panama Canal. Sea-ice seems to be the single biggest contributor to the uncertainty prevailing around ship scheduling and risk perception in the NWP. The chapter has provided a robust methodology for the proposed models to provide a solution to the research questions despite challenges in charting, hydrography, quality, and consistency of ice data in an area where commercial shipping has not even begun, and many have perished in the past! The models had to make assumptions and rely on forecasts due to the ex-ante nature of the study. The study anticipates CAROM to predict the best (least cost) route amongst the three route alternatives based on the ice and navigation data provided. The study stresses the importance of quality of input data to expect a quality output. A workable computer – aided model starts at a distinct advantage in route planning due to the constantly evolving technology aspect. The model will get better data inputs with a much higher resolution satellite imagery in the coming years as the use of drones to map ice fields increases. Charting, multi-beam depth mapping, and better infrastructure will also help in high-quality ENC production at least in the identified shipping routes to design accurate models. Validation and verification process for the CAROM planned with case studies, route validation and ice data simulations should show encouraging results. A full-scale test on board a ship would have been the ideal verification to accomplish in the future with the cooperation of stakeholders. If the CAROM can predict the optimized route as planned, the economic model of the trans-Arctic route will be that much definitive with the proposed Cost-Benefit analysis. It is time to test the CAROM having set up the models as outlined in this chapter.

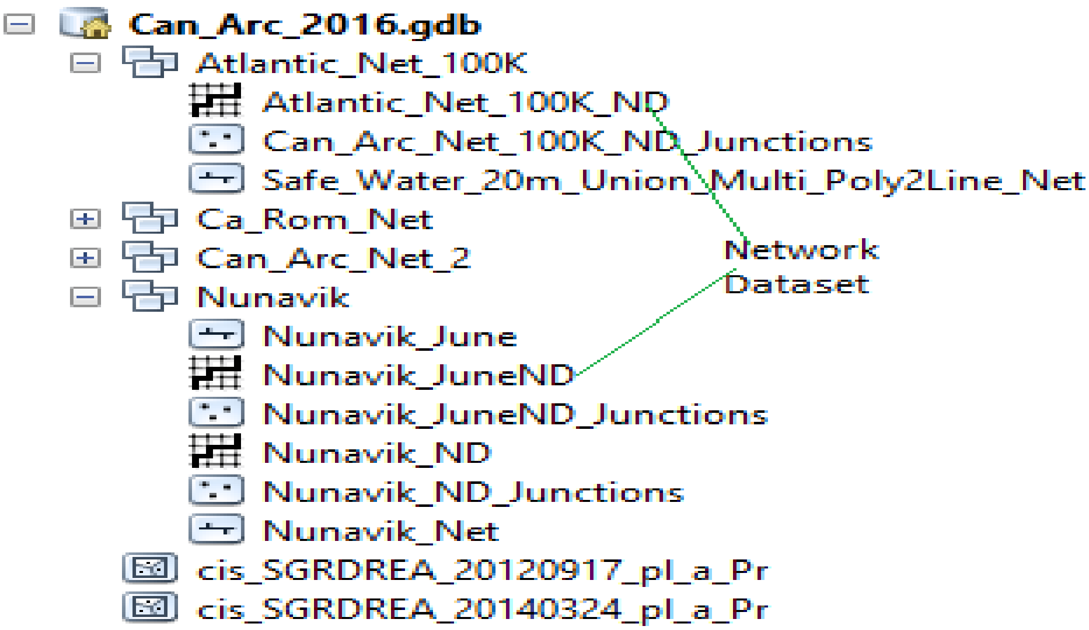
Chapter 4: Results and Discussion

4.1 Introduction

Having outlined the methodology, the Route Model is designed and created with the 'SNZ' base layer and the ice information for the select dates from the CIS datasets. This chapter outlines the procedure to build the models for the two scenarios created for testing the CAROM. The models involving the two ships are tested for two different months in the summer navigation season (June and September) as explained in the two scenarios. Speed data from the Ship Transit-in-ice Model is tabulated in a ship performance table and a speed graph obtained for each ship. The input parameters for the CAROM is recorded with Ice Numerals calculated for each ice regime categorized from the ice datasets.

4.2 Network Dataset- Inputs

A 'Network Dataset' in the Network Analyst (NA) extension created to build the route network and the transportation model is the building block for the 'Route' solver. Of the five separate network analysis classes in the Network Analyst, this study has chosen the 'ROUTE' analysis class for the optimization model. The 'Network Dataset' created for the two ships 'Berge Atlantic' and 'Nunavik' is loaded with the SIGRID-3 ice datasets for June 30, 2014 (Scenario-1), and September 29, 2014 (Scenario-2) in a 'File Geodatabase' (Can_Arc_2016.gdb) created earlier. The feature dataset (Atlantic_Net_100K) in the 'Geodatabase' contains the feature class; the route analysis is conducted on the network built around the feature class. The ‘SNZ’ arrived at through the MCDA-SDSS process (Safe_water_20m_Multi_Poly2Line_net)/ (Nunavik_Net) is the feature class imported in the dataset for building the network. Elements that control navigation in the network is set up as part of the Network attributes, the ‘length’ of each ice regime (a function of speed) allocated the ‘cost’ attribute. As the Network dataset name implies (Figure 15), the Nunavik’s route is analyzed on ‘Nunavik_JuneND’ and Berge Atlantic’s performance tested on ‘Atlanic_Net_100K_ND’ network dataset.



- ⊟ **Can_Arc_2016.gdb**
  - ⊟ Atlantic_Net_100K
    - Atlantic_Net_100K_ND
    - Can_Arc_Net_100K_ND_Junctions
    - Safe_Water_20m_Union_Multi_Poly2Line_Net
  - ⊞ Ca_Rom_Net
  - ⊞ Can_Arc_Net_2
  - ⊟ Nunavik
    - Nunavik_June
    - Nunavik_JuneND
    - Nunavik_JuneND_Junctions
    - Nunavik_ND
    - Nunavik_ND_Junctions
    - Nunavik_Net
  - cis_SGRDREA_20120917_pl_a_Pr
  - cis_SGRDREA_20140324_pl_a_Pr

Figure 15: *Arc Catalog-Network Datasets- ‘B. Atlantic’ and ‘Nunavik.’*

Source: Author

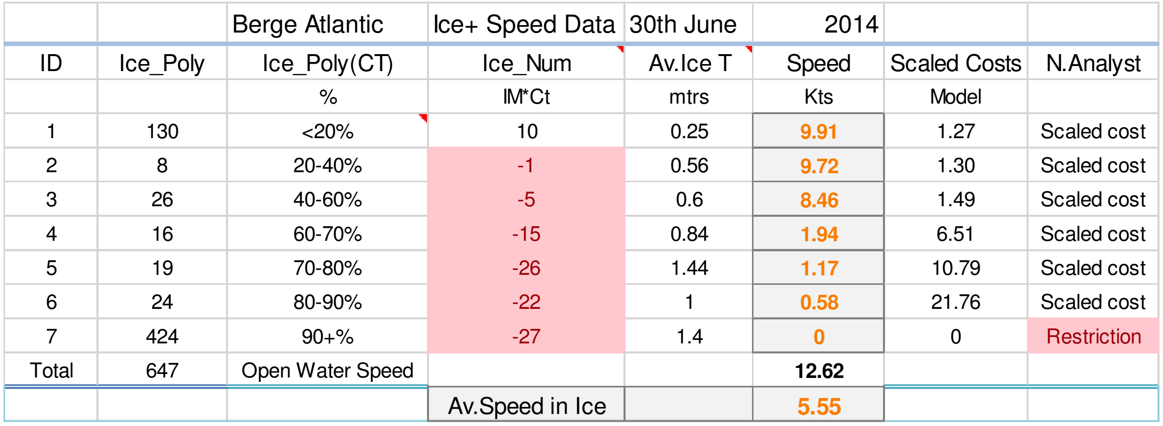
The ice impedance, mapped with the feature layer ‘Polygon Barriers’ in the Network Analyst is a function of ship speed in ice. “Barriers are part of the Network analysis layer and not of the Network Dataset” (ESRI, 2016) but can be edited in the Network Dataset without access to any editing privileges. The ability to alter the barrier impedance has a distinct advantage in voyage planning since the resistance offered by ice is a variable phenomenon and may change during the voyage. The analyst is thus able to alter the impedance ratio with the changing ice conditions on the 'fly' if required.

4.2.1 Scenario-1

The ice dataset from 30 June 2014 is loaded as 'Polygon Barriers' ('Restriction and 'Scaled Cost') arranged in seven categories based upon ice coverage (CT) numbers. The barriers represent impedance along the route, the magnitude of which is a function of the level ice resistance in each ice regime. 'Restriction' barriers are non-traversable and have a default value of Zero (0). 'Scaled Cost' barriers are traversable and have a default value of one (1). The combined chart of the Eastern and Western Arctic yielded six hundred forty-seven (647) ice polygons that were analyzed to produce inputs for the Network Dataset (Table 13). The performance of each ship compared in each scenario and the two scenarios analyzed as they represent two distinct ice datasets.

Table 13

Network Dataset-Input Parameters- 'Berge Atlantic' (June)



		Berge Atlantic	Ice+ Speed Data	30th June	2014		
ID	Ice_Poly	Ice_Poly(CT)	Ice_Num	Av.Ice T	Speed	Scaled Costs	N.Analyst
		%	IM*Ct	mtrs	Kts	Model	
1	130	<20%	10	0.25	9.91	1.27	Scaled cost
2	8	20-40%	-1	0.56	9.72	1.30	Scaled cost
3	26	40-60%	-5	0.6	8.46	1.49	Scaled cost
4	16	60-70%	-15	0.84	1.94	6.51	Scaled cost
5	19	70-80%	-26	1.44	1.17	10.79	Scaled cost
6	24	80-90%	-22	1	0.58	21.76	Scaled cost
7	424	90+%	-27	1.4	0	0	Restriction
Total	647	Open Water Speed			**12.62**		
			Av.Speed in Ice		5.55		

Source: Author

Two tables are thus generated per scenario, one for each ship that includes the Ice Numerals/RIO, average ice thickness, and estimated speed per ice coverage category. The IN's are calculated as per the AIRSS methodology and the RIO's as per the POLARIS, but the IN numbers are shown here for the sake of conciseness and brevity. The appropriate Ice Multiplier is chosen from the Ice Multiplier table and the Ice Numeral calculated for each vessel class. The stage of development data (SA, SB, SC) is converted for each partial concentration (CA, CB, CC) attribute by replacing the SIGRID-3 schema codes with ice thickness numbers and then averaged to get the size of ice per ice coverage (CT) class. The average ice thickness is required not only to calculate the IN numbers but remains a critical parameter for Ship-transit model in level ice. The modified Riska methodology is applied subsequently to estimate the ship speed in each ice concentration (CT) category. The Ice thickness Vs speed graph as calculated by the Ship-transit Model

Of ‘Berge Atlantic’ (Figure 16) shows the predicted speed (ʊ̈́) in various ice thicknesses, a function of the net thrust (engine capacity) and the resistance in level ice.

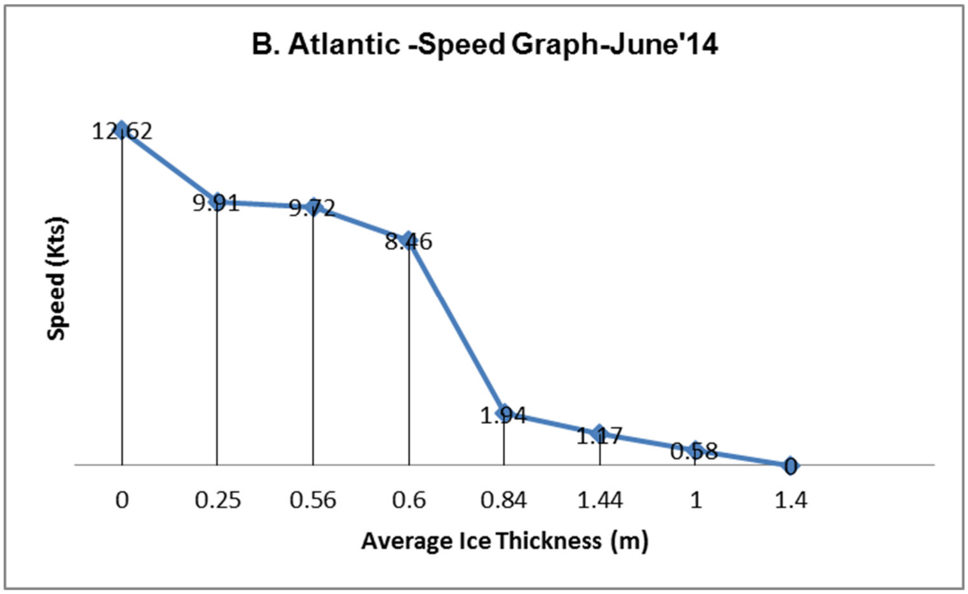


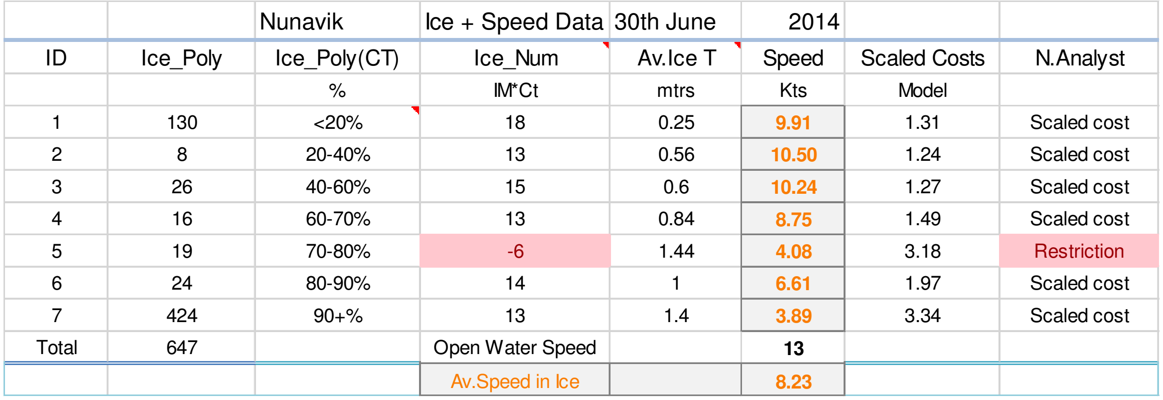
Figure 16: *Ice thickness Vs Speed graph- ‘Berge Atlantic’ (June)*
Source: Author

The reduction in speed due to the resistance offered by sea-ice in the various ice regimes/ ice polygons is modelled as a ratio in the Network Analyst and acts as a hierarchy attribute. The ratio of open water speed to the calculated speed in each ice concentration shows the magnitude of resistance termed ‘scaled cost’ in the model for areas with aggregate positive speed. The ‘Berge Atlantic’ is modelled to go into all the ice regimes except where coverage exceeds 9/10th ice (CT> 90%); the speed has dropped to zero and modelled as ‘Restriction’ as higher ratios denote heavier impedance and reduced speed (Table 14). As per AIRSS, vessels are advised not to proceed without icebreaker escort in areas of negative Ice Numerals (IN<0). For the ‘Berge Atlantic,' a Category ‘C’ ship, all areas except one (CT<20%) shows negative IN. If modelled as ‘Restriction,' the CAROM will not offer any optimized route solution since the ice regime was too unsafe for the vessel to proceed even though it had positive speed in most of the ice regimes. The study has placed a ‘scaled cost’ exactly for the above reason to test out the model whereas the ship required an icebreaker escort to complete the passage in a real operational situation. The CAROM should predict an optimized solution with the network activated, and the results analyzed.

The calculations for the MV ‘Nunavik’, a Category ‘A’ ship look entirely different for the same ice chart of 30 June 2014:

Table 14

Network Dataset-Input Parameters- ‘Nunavik’ (June)



		Nunavik	Ice + Speed Data	30th June	2014		
ID	Ice_Poly	Ice_Poly(CT)	Ice_Num	Av.Ice T	Speed	Scaled Costs	N.Analyst
		%	IM*Ct	mtrs	Kts	Model	
1	130	<20%	18	0.25	9.91	1.31	Scaled cost
2	8	20-40%	13	0.56	10.50	1.24	Scaled cost
3	26	40-60%	15	0.6	10.24	1.27	Scaled cost
4	16	60-70%	13	0.84	8.75	1.49	Scaled cost
5	19	70-80%	-6	1.44	4.08	3.18	Restriction
6	24	80-90%	14	1	6.61	1.97	Scaled cost
7	424	90+%	13	1.4	3.89	3.34	Scaled cost
Total	647		Open Water Speed		**13**		
			Av.Speed in Ice		8.23		

Source: Author

The fact that only one ice regime (70% <CT ≤ 80%) could be found on a negative IN explains the ice classification, being a ‘PC4’ class it can navigate independently in much thicker ice regimes. The rest of the ice regimes bear high positive IN’s and the ‘Polygon Barriers’ feature layer is modelled as ‘scaled cost’ in all but the one with negative IN

(IN= -6). It is interesting to note that the Ship-transit Model predicted a positive speed over the ground but recommended an unsafe area as per AIRSS for autonomous navigation. The ship performance can only be judged with the CAROM activated and results analyzed.

A quick check with POLARIS methodology, on the other hand, considers this area to be a navigable zone (RIO= +6). The AIRSS and POLARIS tables show a subtle difference between the TFY-MYI range as far as the IM/RV values are concerned. The Ship-Transit speed model has predicted the following graph:

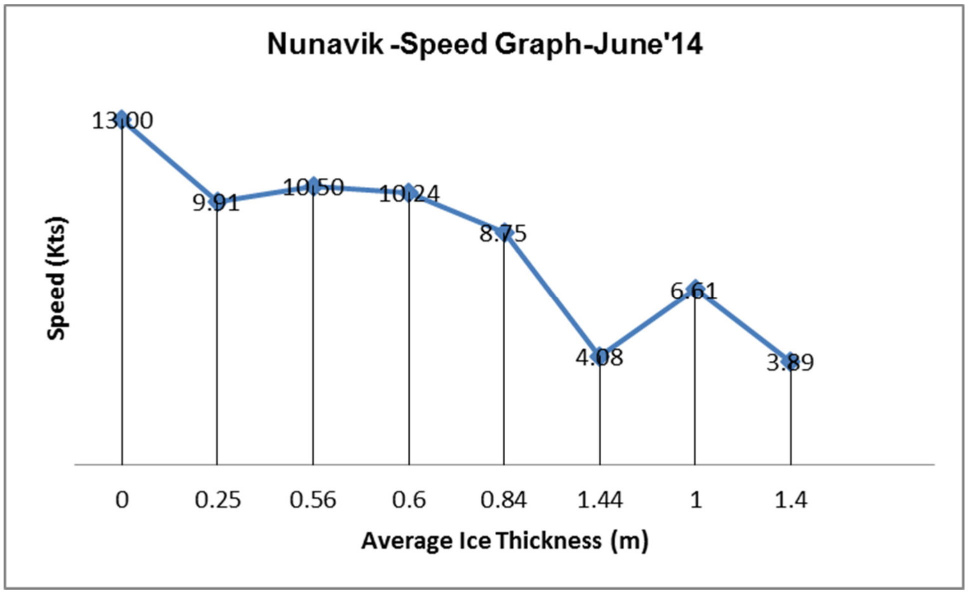


Figure 17: *Ice thickness Vs Speed graph- 'Nunavik' (June)*

Source: Author

The underlying assumption in the graphs is that the level ice resistance varies linearly (Kotovirta et al., 2008) with speed. Although ice by far is the more predominant factor that affects speed (Mulherin et al., 2009) among all environment variables, the assumption needs further full-scale model tests and empirical analysis (Riska et al., 2013) to establish a cogent relationship. The impedance factor is the ratio of open water speed to the calculated speed in the ice regime and establishes the hierarchy attributes for the algorithm in the eventual mapping of the route of least impedance. A closer inspection of the speed graph for both ships indicates relatively slower speed in the least ice concentration category (CT<20). A prudent ice-navigator would navigate with extreme caution in such waters due to the presence of numerous icebergs[61]and possibility of contact with floe-bergs and growlers remain high. The visibility in higher Arctic latitudes may be restricted severely due to fog and navigation during reduced daylight and darkness poses additional challenges requiring constant use of aids to navigation such as Radars. The ice datasets also indicate the presence of ice floes in certain ice polygons. Ice floes (different sizes) are identified and modelled as ‘Restriction’ in the feature layer ‘Polygon Barriers’ as the ship would avoid such areas. In the absence of an iceberg chart of the Canadian Arctic, the icebergs are modelled as ‘Polygon Barrier’ feature layer instead. CIS does not produce Iceberg Charts north of 60° N (Environment and Climate Change Canada-A, 2016), neither is information provided on growlers and bergy bits. Increased shipping activity in the Canadian Arctic may result in the issuance of Iceberg Charts north of 60°N that will certainly make navigation much safer.

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[61] Icebergs-June data-set: 21 icebergs reported as per the ice chart in ice regime (CT<20%)

4.2.2 Scenario-2

SIGRID-3 ice dataset from 29 September 2014 is made use of in this scenario (Table 15) having the same ships with the ice polygons arranged in eight separate categories.

Table 15

Network Dataset-Input Parameters- 'Berge Atlantic' (September)

		Berge Atlantic	Ice+Speed Data	29th Sept	2014		
ID	Ice_Poly	Ice_Poly(CT)	Ice_Num	Av.Ice T	Speed	Scaled Costs	N.Analyst
		%	IM*Ct	mtrs	Kts	Model	
1	50	<20%	12	0.25	9.91	1.27	Scaled cost
2	20	20-40%	20	0.04	9.91	1.27	Scaled cost
3	13	40-50%	12	0.2	9.91	1.27	Scaled cost
4	11	50-60%	1	0.5	7.97	1.58	Scaled cost
5	2	60-70%	-12	1	1.75	7.21	Scaled cost
6	25	70-80%	16	0.3	8.55	1.48	Scaled cost
7	55	80-90%	-4	0.7	3.50	3.61	Scaled cost
8	199	90+%	-34	1.4	0	0	Restriction
Total	375		Open Water Speed		12.62		
			Av.Speed in Ice		7.13		

Source: Author

The ice conditions indicate a much better ice regime since the 'Berge Atlantic' must contend with three ice regimes with negative Ice Numerals compared to six regimes in the June chart. The average ice thickness is considerably better, besides the speed through the ice regimes. The September month is historically the best month (NSIDC-A, 2016) for reduced ice coverage and thickness and the charts indicate as much for 2014.The number of ice polygons is far less in September (375) than June (647). The 'Berge Atlantic,' a Category 'C' ship may require reduced icebreaker assistance than the month of June as per the IN values. The 'safe speed' practice (Enfotec Technical Services Inc., 1996) adopted in relatively open waters (CT<20%) is also observed in the September month due to reported presence of icebergs[62]and likelihood of floe-bergs and growlers in such waters that are not mapped on the charts; extreme caution is warranted as a consequence. Ice floes (medium and vast size) are mapped and marked as ‘Restricted’ on the ‘Polygon Barrier’ feature layer and expected to contribute to the route optimization calculation in the CAROM model. The results will prove how the ship performs with the CAROM activated and the algorithm tested.

The speed graph for the ‘Berge Atlantic’ in Scenario-2 (September voyage) shows a speed reduction of about 20% in ice infested open waters (CT< 20%), a decision to be taken by the Shipmaster from expert knowledge and may vary with experience in ice and ship type. The estimated speed for the rest of voyage follows the speed calculation formulae as discussed earlier. The vessel attained zero speed with 9/10+ ice coverage and predicted to have a high negative Ice Numeral (-34). The voyage plan could cater for planning an icebreaker well in advance of negotiating the heavy ice regimes. Voyage planning with optimized routeing will allow the NORDREG authorities in asset mobilization, planning, and deployment of icebreaker (Canadian Coast Guard-A, 2013) well in advance as resources may be thinly stretched in the Northwest Passage.

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[62] Icebergs-September data-set: 23 icebergs reported in CT<20%

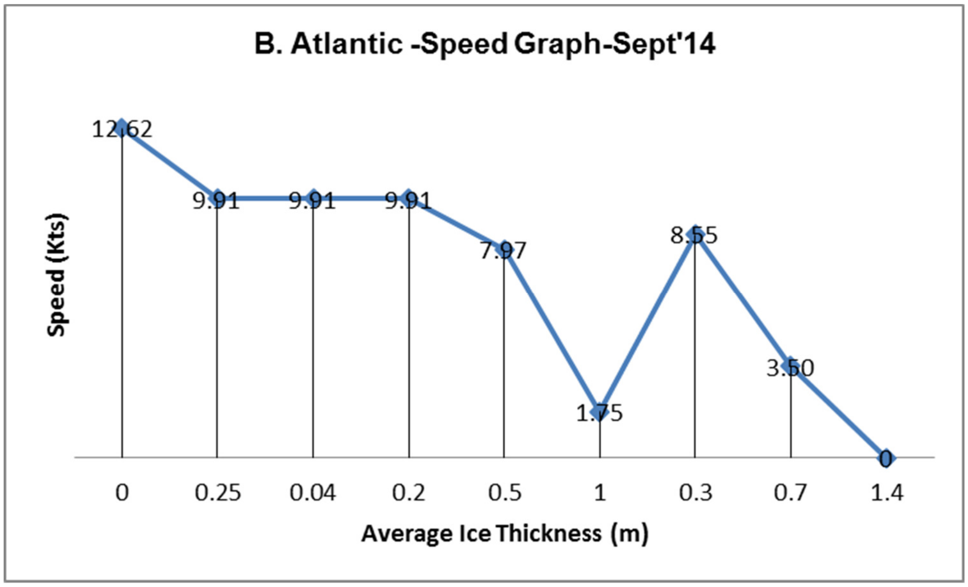


Figure 18: *Ice thickness Vs. Speed graph- 'Berge Atlantic' (September)*

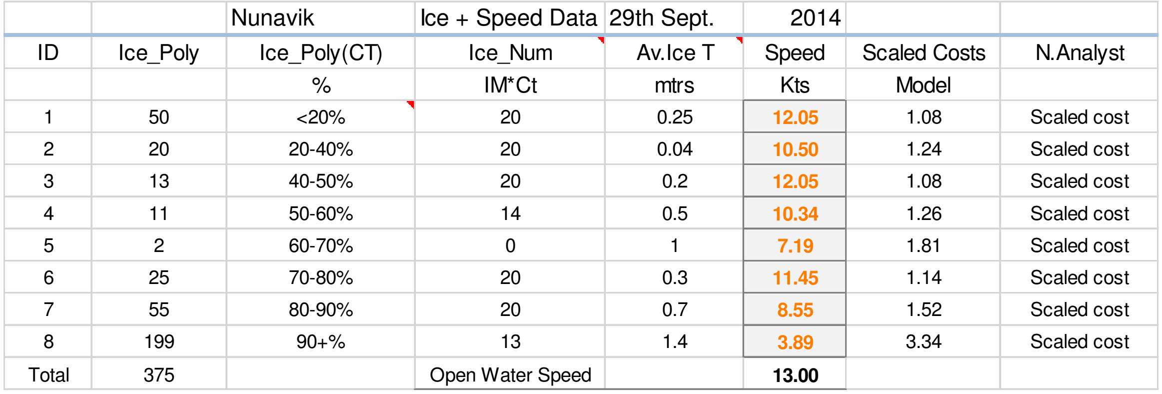
Source: Author

Increased shipping traffic in the future will put additional pressure on the authorities unless assets such as icebreakers increased in number (Parsons, 2010) and deployed strategically.

MV 'Nunavik' fares much better in the September voyage (Table 16) when compared with the June voyage. The vessel has recorded high positive Ice Numerals in seven of the eight categories and ensured a navigable Ice Numeral (IN=0) in the remaining ice regime.

Table 16

Network Dataset-Input Parameters- 'Nunavik' (September)



		Nunavik	Ice + Speed Data	29th Sept.	2014		
ID	Ice_Poly	Ice_Poly(CT)	Ice_Num	Av.Ice T	Speed	Scaled Costs	N.Analyst
		%	IM*Ct	mtrs	Kts	Model	
1	50	<20%	20	0.25	**12.05**	1.08	Scaled cost
2	20	20-40%	20	0.04	**10.50**	1.24	Scaled cost
3	13	40-50%	20	0.2	**12.05**	1.08	Scaled cost
4	11	50-60%	14	0.5	**10.34**	1.26	Scaled cost
5	2	60-70%	0	1	**7.19**	1.81	Scaled cost
6	25	70-80%	20	0.3	**11.45**	1.14	Scaled cost
7	55	80-90%	20	0.7	**8.55**	1.52	Scaled cost
8	199	90+%	13	1.4	**3.89**	3.34	Scaled cost
Total	375		Open Water Speed		**13.00**		

Source: Author

The average speed in ice has registered an increase (ΰ=9.5 Knots), and it remains to be seen which, of three route alternatives the CAROM would predict under the given conditions. The speed graph for September (Figure 19) registers a marked improvement over the June voyage although the reduction in speed in ice infested open waters (CT<20%) is due to the presence of icebergs and the likelihood of encountering floe bergs and growlers. The speed inputs for low ice coverage areas (<50%) is taken from the actual speed registered by the ship as reported to NORDREG during the voyage and the remainder is calculated from the formula.

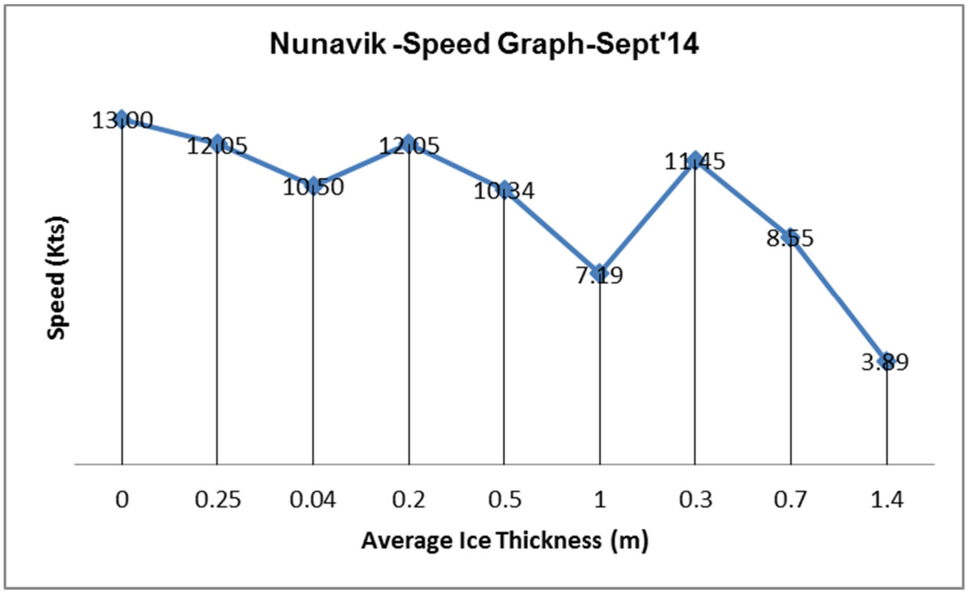


Figure 19: *Ice thickness Vs. Speed graph- 'Nunavik' (September)*

Source: Author

The intra-annual variability in ice thickness (Stephenson et al., 2013; Maslanik et al., 2007) is excluded from these calculations, and uniform thickness is assumed between June and September 2014 for ice regimes beyond First-year Ice (FYI) indicating an apparent weakness in the model.

4.3 Findings

4.3.1 Validation: Results

The study has reconstructed the 'Nunavik' voyage with the help of waypoints available from Nunavik's Log Book (Fednav, 2014) and NORDREG reports.The actual voyage is compared with the optimized route generated by CAROM based upon the ice datasets of

29 June 2014. The Network Dataset input parameters for the model remain the same as the one conducted in the Scenario-2 analysis (section 4.2.2).

The 'Nunavik' had transited the NWP between 23rd September 2014 (72.15 N, 070.38W) and 28th September 2014 (71.00 N, 133.00 W) on a trans-Arctic voyage from Deception Bay (Quebec, Canada) to Bayuquan (China) with a cargo of Nickel concentrate (The Northern Miner, 2014).

The route network optimization model (CAROM) returned the following data output; results that corroborate the research objectives namely:

a. Predicted the best route (POWS route) allowing for the navigational constraints and available ice conditions.
b. Minimized interaction with sea ice, ice floes, and icebergs to the best possible extent.
c. Calculated the estimated speed through ice resulting in better voyage planning and route economy.
d. Predicted Ice Numerals, thus resulting in better planning and resource mobilization.

A comparative assessment of the actual voyage and the CAROM results is presented hereunder:

Table 17

Results: 'Nunavik' Voyage Vs. CAROM output

VALIDATION		
Objective	**Nunavik Voyage**	**Model Output**
Choice of Route	**POWS Route**	**Optimized-POWS Route**
Ice Interaction	**Visual & Ice Charts**	**Voyage planned with Ice datasets**
Estimated Speed(Kts)	**11.5**	**9.5**
IN/RIO	**On board Calculation**	**Calculated in advance**
Distance(NM)	**1345**	**1375**
Transit Duration(Days)	**4.9**	**6.0**

Source: Author

4.3.1.1 Limitations and assumptions

There are several limitations in the validation study related to data availability and model input:

a. The ice datasets should ideally have been analyzed for each day (23rd to 28th September) of the 'Nunavik' passage for best accuracy. The SIGRID-3 ice datasets are currently available once a week and the closest ice dataset available was on 29 September 2014.

b. Assumed that the ice regimes during the original passage would not have been drastically different from modelled.

c. The daily position report (1600 Z) NORDREG also includes the speed of the ship with the assumption that the reported speed in ice is averaged over the last 24 hours.

d. Lack of substantive empirical data from vessels engaged in ice navigation is a major problem that the route model must contend with in the study, more so in the

> NWP. Nunavik is reported to be the first commercial cargo vessel to have transited the ‘POWS’ since the S.S. Manhattan in 1969 (Fednav, 2014) One should stick to an ex-ante approach for the time being until shipping traffic improves gradually as projected this century.

The optimized route shows (Figure 20) the interaction with various ice regimes along the way that includes avoiding areas of heavy ice floe concentration (hatched brick red) in the Parry Channel east of the Prince of Wales Strait.

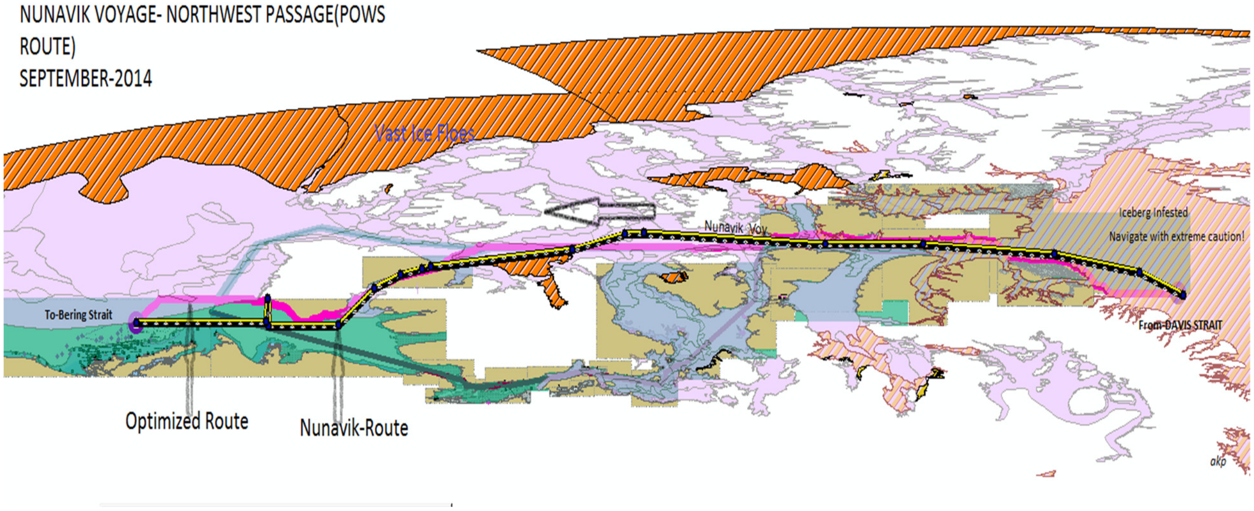


Figure 20: *‘Nunavik’ Route vs. Optimized Route.*

Source: Author

Both the ‘Nunavik’ route and the CAROM route follow the ‘POWS’ that affirms that the ice chart used for route optimization did not differ substantially from the actual ice conditions a few days earlier. The optimized route is computer generated and seen to avoid thicker ice areas along the way as it charts the route over the safe layer of water.

The computer-generated route is not as smooth as a manually plotted ‘Nunavik’ course line since it generates multiple waypoints with electronic precision while considering all the constraints. The course line is smoothened by the ‘Simplify Line’ geoprocessing tool to render it practically useful for navigation at sea. The tool removes the extraneous bends, the intrusions, and extrusions but maintains the shape of the course line. The new course line is inspected thoroughly to check if the Douglas-Peucker[63] algorithm used for route simplification has not strayed into unsafe areas. The geoprocessing tool allows the user to vary the degree of simplification, editing vertices to maintain a balance between route safety and course line smoothening. A complete manual inspection of the route is carried out with each ‘Simplify Line’ operation for this purpose.

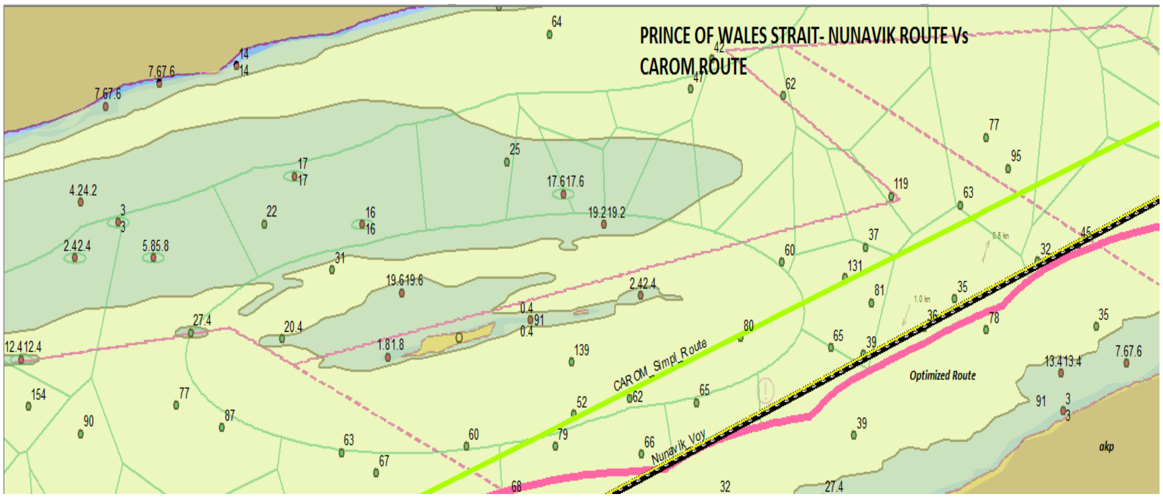


Figure 21: *Prince of Wales Strait: ‘Nunavik Route’ Vs. ‘Simplified Route.’*

Source: Author

A snapshot of the routes in the ‘POWS’ (Figure 21) shows the respective position and shape of the optimized (Pink) and ‘simplified’ route (Green line) with the ‘Nunavik’ route

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[63] Douglas-Peucker Algorithm: used for ‘Line Simplification’ in ArcGIS

overlain. The S-57 ENC depicts charted area covered with more than 9/10th ice, charted depths, shallow water soundings, and the Princess Royale Island. The ‘simplified’ course line has breached the 2NM safety buffer near the eastern extremity of the island. The smoothened course line could be further adjusted by creating an additional vertex, and the line shifted, but with the current draft (11.8 meters) of the ‘Nunavik, it is considered relatively safe for navigation. The ‘Simplify Line’ algorithm does have shortcomings, and a thorough inspection of the route is necessary to ensure the best trade-off between route optimization and efficient navigation. The optimized distance is slightly longer (1375NM) than the actual voyage (Table 17) and the calculated speed in ice estimated at 9.5 Knots. The optimized voyage puts the transit time for CAROM at six days, a day longer than the ‘Nunavik.' The distance and speed determination in ice are the most critical element that guides voyage economics since it is easier to estimate fuel economics besides the planned scheduling of the vessel, paramount to the shipping company.

4.3.2 Transit Case Study: Results

The ‘origin’ (74N, 80W) and ‘destination’ (71.5 N, 128.57 W) points for the case study in the NWP is kept the same for both ships and the CAROM.

The CAROM undergoes a rigorous test (four times) with two ice datasets simultaneously for each ship with the following results:

Table 18

Results: Transit Case Study: Scenario outputs

		Transit Case Study-Results					
Date of Transit	**Scenarios**	**Optimized Route**	**Ship**	**Distance(NM)**		**CAROM**	**Transit Time**
				Plotted	Optimized	Av.Speed (Knots)	Days
30/06/2014	1	**No Solution**	B.Atlantic	**941**	**NA**	**5.55**	**NA**
		POWS	Nunavik	**941**	**1013**	**8.23**	**5.1**
29/09/2014	2	**No Solution**	B.Atlantic	**941**	**NA**	**7.13**	**NA**
		POWS	Nunavik	**941**	**1037**	**9.5**	**4.5**

Source: Author

Each ship has a separate ‘Network Dataset’ of its own with the June and September ice data sets loaded and saved in two separate ‘ArcMap’ files for ease of spatial analysis and route mapping. The Route Optimization Model (CAROM) predicts the ‘POWS’ route for the ‘Nunavik’ in June and September but fails to give any route solution for the ‘Berge Atlantic’ (Table 18). A closer investigation of the ice concentration categories in June (section 4.2.1) reveals that 65% of the total ice polygons had more than 9/10th sea coverage with ice thickness averaging 1.4 meters and an Ice Numeral value of -27. The vessel being a Category ‘C’ ship is also underpowered to negotiate this ice regime and shows an effective speed of zero. The ‘Route’ solver investigates options on all three route alternatives but fails to find a favourable ice regime to predict an optimized route (Figure 22).

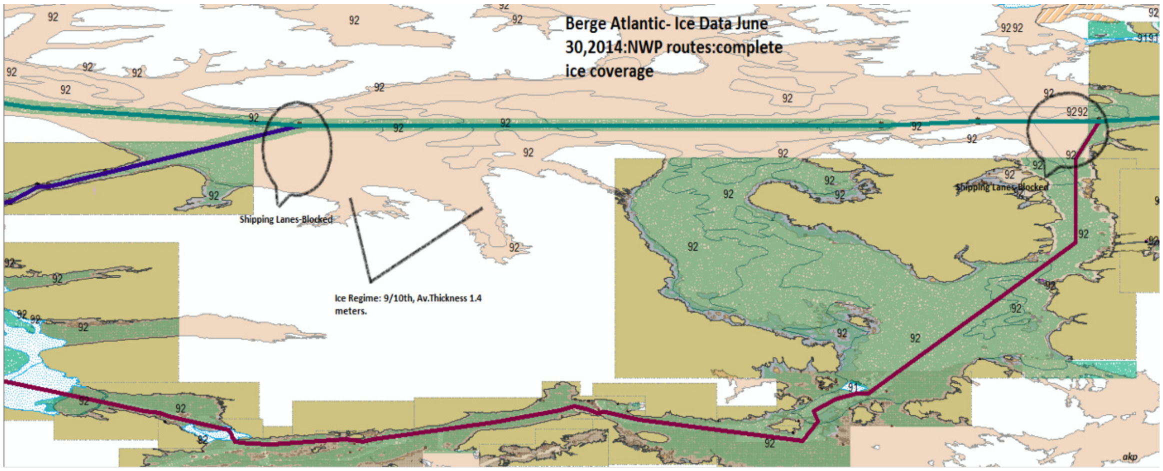

Figure 22: '*Berge Atlantic' June Voyage- Routes blocked due ice*

Source: Author

In fact, all but one category returns a positive IN that indicates a Category 'C' vessel would not have completed the voyage without an icebreaker escort on June 30, 2014.The conditions in September seem comparatively better as far as ice impedance is concerned but still not good enough (Figure 23) for the Category 'C' vessel to negotiate any of the routes in the NWP. More than 9/10th ice coverage could be seen in 53% of the ice polygons (section 4.2.2) having a negative Ice Numeral (IN= -34) with an effective speed of zero.

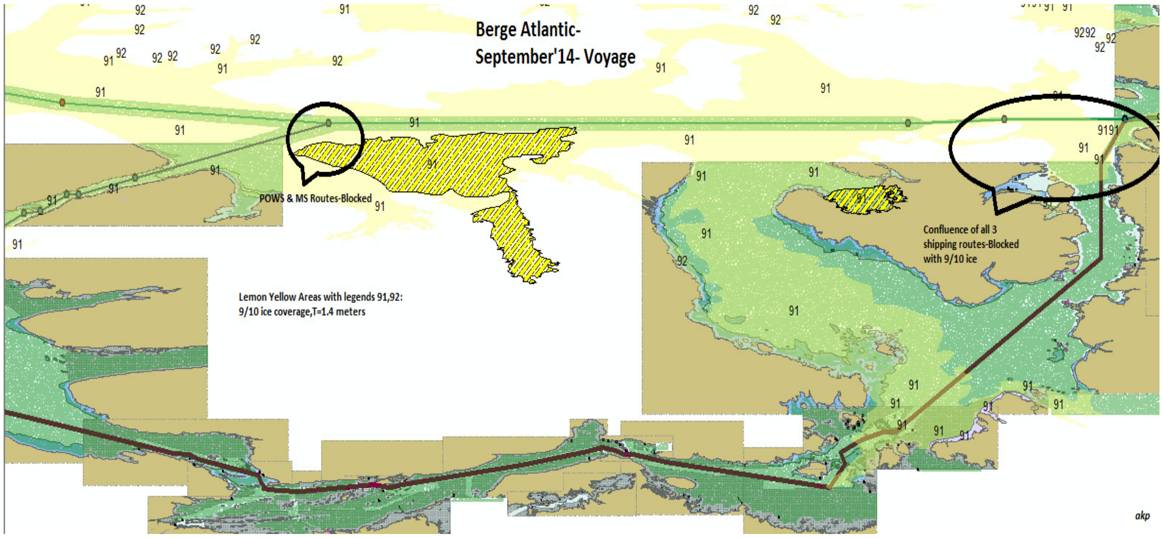

Figure 23: *'Berge Atlantic'-September Voyage- Routes blocked due Ice*

Source: Author

The Category 'A' ship, the 'Nunavik' can complete the passage successfully as the CAROM data indicates. The POWS passage being is the shortest among all the routes remains the passage of choice; the actual distance sailed ('simplified' route) is much longer, though, since the optimized route predicts the journey along the 'SNZ' through areas of least ice resistance generating multiple waypoints in the process. The September ice data and the estimated average speed (9.5 Knots) are better than the June statistics as is reflected in the Ice Numeral numbers. The month of September being the month of least ice extent historically (NSIDC-A, 2016), is reflected in the ship's voyage performance as well. Consequently, the transit time calculated is 4.5 days. An obvious advantage of the CAROM is that the Shipmaster is aware of the predicted optimized route and the ice regime situation before entering the ice edge. The predicted route assists in the ship planning for icebreaker assistance as deemed fit in conjunction with NORDREG.

The difference in distance (POWS route) observed in the Validation Study (section 4.3.1) and the Transit Case Study (section 4.3.2) is due to different ‘origin’ and ‘destination’ coordinates. The Validation study applied the same coordinates in the NWP as the MV ‘Nunavik’ to ensure parity.

4.3.3 Simulation: Results

The CAROM model did not offer a route solution for the Category ‘C’ ship due to the presence of thick ice completely covering the ‘Safe Navigation Zone’ in the NWP. The voyages can, however, be simulated and the veracity of the algorithm checked by incrementally reducing the impedance (‘Restriction’ to ‘Scaled Costs’) and shifting them around to check all the three routes. Changes in ‘Scaled Costs’ values in the ‘Network Dataset’ can have a significant impact on the route selection as well as coordinates within a route. Simulations carried out with ‘Line Barrier,’ and ‘Point Barrier’ feature layers yield interesting results. The shape of the feature layer chosen depends on the shape and spatial extent of the features involved. A flotilla of growlers or presence of an iceberg reported on the routes is modelled as ‘Line Barrier’ and ‘Point Barrier’ respectively. Thus, a Category ‘C’ ship is simulated for an all-weather passage through the NWP where a Category ‘A’ vessel may have difficulty negotiating icebergs in the summer. Such iterative simulations could come in very handy to train future Arctic ice-navigators on ship simulators.

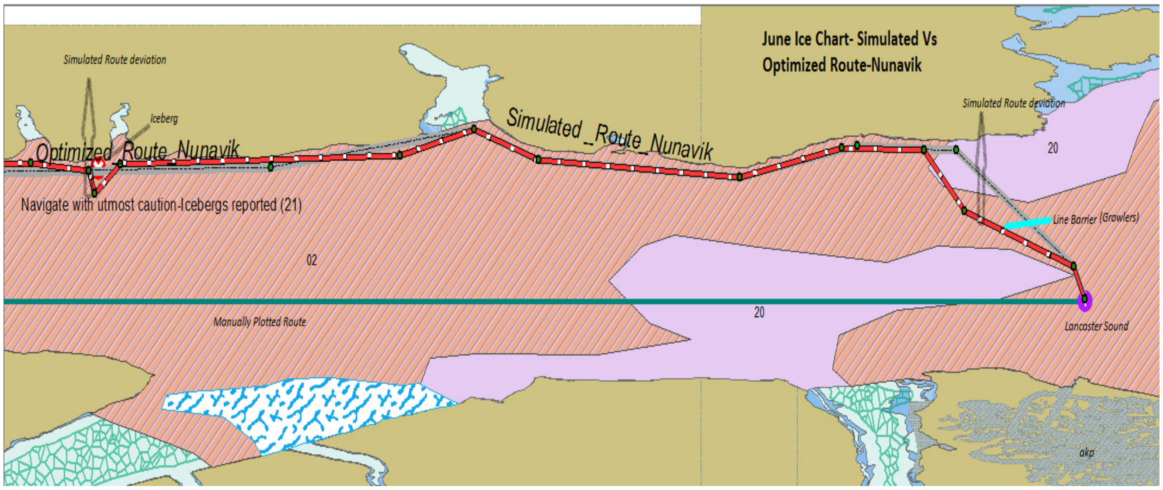

Figure 24: *Simulated Vs. Optimized Route- 'Nunavik.'*

Source: Author

The simulated route (Figure 24) deviates around an area of growlers (Line Barriers) and an iceberg in Lancaster Sound from the optimized route of the 'Nunavik' as marked on the chart. The manually plotted course line (blue) as plotted on the 'Safe Navigation Zone' is drawn assuming open water for comparison purposes.

Route simulation is also conducted with the September ice datasets and the Category 'C' vessel 'Berge Atlantic.' The vessel failed to make the passage due to a tough ice regime in the Transit Case Study observed earlier. A two-step simulation is performed as follows:

a. In this stage the ice polygons that aborted the passage (CT> 90%) are removed from the 'Network Dataset' since this category comprised about 53%, a significant area that contributed to heavy ice resistance. The 'Route' solver activated to recalculate the voyage predicts an optimized route through the M'Clure Strait (Figure 25).

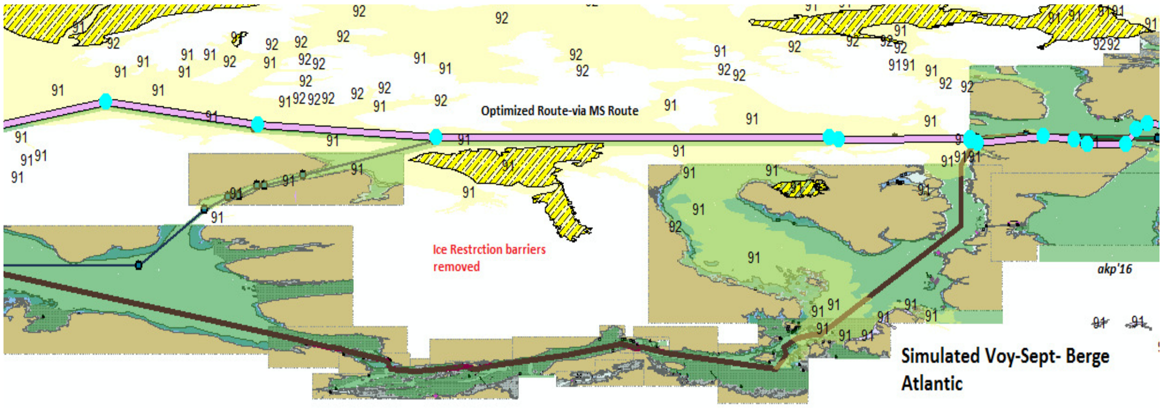

Figure 25: *Route Simulation M'Clure Strait – 'Berge Atlantic.'*

Source: Author

b. In this stage, a restriction 'Line Barrier' placed across the 'MS' route in the Parry Channel and the route is recalculated again. The optimized route shows a solution through the 'PS' Route (Figure 26) that proves the decision-making ability of the CAROM with simulated impedances.

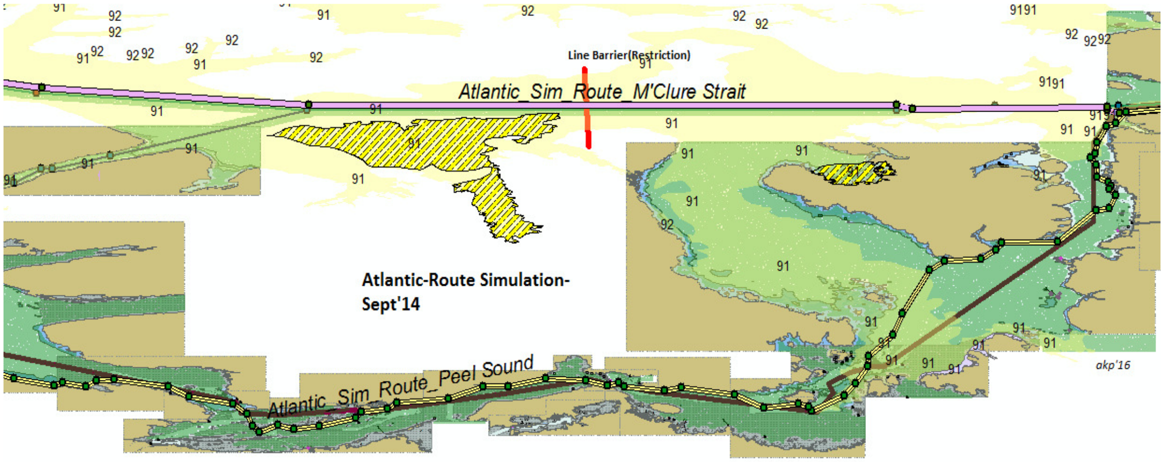

Figure 26: *Route Simulation Peel Sound Route – 'Berge Atlantic.'*

Source: Author

The results of the simulation study (Table 19) compare all the three routes, the simulated distances and average speed as calculated for each route.

Table 19
Results: CAROM Route Simulation

Simulation-Results							
Date of Transit	**Optimized Route**	**Ship**	**Distance(NM)**		**CAROM**		**Sim-Transit**
			Plotted	Optimized	Simulated	Av.Speed (Knots)	Days
30/06/2014	**POWS-Route**	Nunavik	**941**	**1013**	**1032**	**8.23**	**5.2**
29/09/2014	**MS-Route**	B.Atlantic	**949**	**NA**	**1012**	**7.36**	**5.7**
	PS-Route		**1282**	**NA**	**1420**	**7.36**	**8.0**

Source: Author

The simulated transit time also shows the route alternatives, as predicted by the model based on the simulated impedances in the Network Analyst.

4.4 Risk Mitigation and CAROM

The Arctic region occupies an iconic status in the global geography, known more for its remoteness, ecological biodiversity, and frozen seas. It is also extremely rich in natural resources that remain largely untapped as climate change and technological progress have brought the commercial importance of Arctic firmly in focus (Lloyd's, 2012). The diminishing sea-ice remains an existential threat to navigation as ship traffic in the Arctic increases progressively this century. The Arctic environment is highly sensitive to damage and is prone to suffer long-term impacts of events such as oil pollution. There can be many types of pollution including ship-sourced oil pollution due to contact damage with ice, ship grounding, and even ship sinking. Significant knowledge gaps exist in cleaning up oil from the cold and the enclosed Arctic Ocean, the long-term effects of such an eventuality even less understood. Ice avoidance and prevention of pollution is the key to risk mitigation in the fragile Arctic ecosystem. There are many enhanced risks that ships may face in the NWP over and above the normal risks encountered in sub-Arctic waters. They may include inter-alia ice contact, poor hydrography, and surveys, lack of ENC coverage, poor satellite communication, and lack of maritime infrastructure (repair facilities, Port of Refuge). The last few years witnessed substantive progress achieved in addressing the international regulatory framework governing the Arctic with the adoption of the safety and environmental parts of the IMO Polar Code. A broad spectrum of areas covered includes ship design, construction, training needs of seafarers, ship operations, and pollution prevention while considering the existing provisions of MARPOL and SOLAS. The implementation of the Polar Code will enhance safety and environmental protection for remote operations in routine and extreme conditions. Development of a decision-making system meant for voyage planning in the form of POLARIS championed by the IACS is underway. The POLARIS presents a risk assessment tool for assessing operational limitations during ice navigation and provides a framework for further enhancements (IMO MSC.94/3/7). The CAROM tabled in this study takes another step in the domain of risk assessment and mitigation by developing a route optimization system taking on board all the concepts enumerated in the Polar Code and the POLARIS framework.

Chapter 5: Economics- Northwest Passage

5.1 Introduction

Commercial shipping is demand driven and goes wherever water flows. The case of maritime transport in the Northwest Passage is an apt example of ships venturing into waters where so many perished as the area had been frozen with ice and regarded as the 'Holy Grail' by explorers. Diminishing sea ice has triggered diverse economic activities within the resource-rich Arctic that in turn provides the opportunity for transportation of goods. The fluvial mode is the cheapest and most environment-friendly transport among all forms of transport including Air, Road, and Rail (Stopford, 1997). The central focus of this study is facilitating shipping in the NWP because this segment remains the untested link between the Atlantic and the Pacific Ocean for a ship on a transit route between NW Europe (Rotterdam) and NE Asia (Tokyo). For this chapter, the study considers the NWP segment to include the ice-infested waters of Lancaster Sound (72.25 N, 70.66 W) to Bering Strait (66.07 N, 169.15 W) about 2400 NM. The 'POWS' is the preferred route of transit for distance calculation purposes as demonstrated earlier with the CAROM. This route constitutes about 31% of the total distance (7850 NM) between Rotterdam and Tokyo, the two ports identified for analysis. The speed and hence the time of transit in the open water segment of the two oceans is well documented and can be estimated if the distance between the ports (AXS Marine,2016) is known. The Route Optimization process and speed determination with ship transit-in-ice model have provided the answer to the time of transit in the NWP. The author assumes, the CAROM to extend beyond the boundaries of the Canadian Archipelagic Area to include the Beaufort Sea and Bering Straits for the sake of brevity and ease of economic analysis.

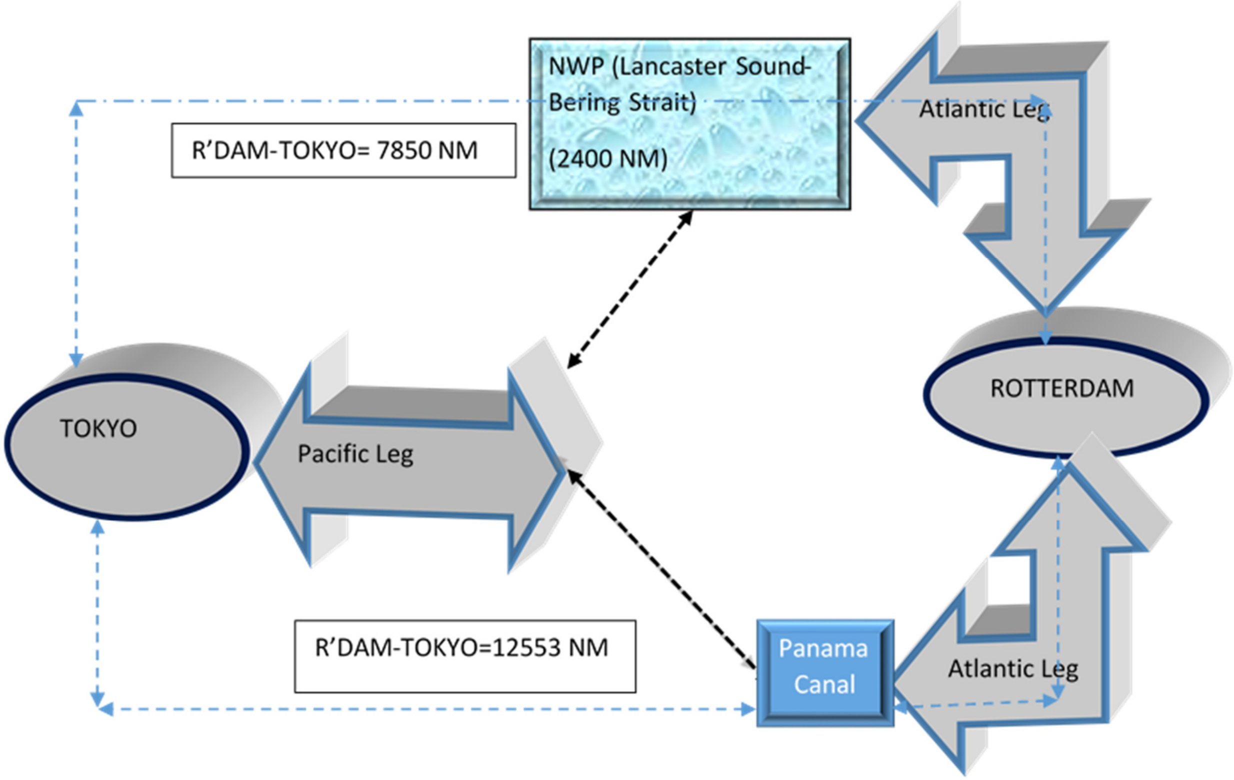

Figure 27: *Trans-Arctic Shipping Route (Rotterdam-Tokyo)*

Source: Author

5.2 Cost-Benefit Analysis: NWP Vs. Panama Route

Since the beginning of the 20th century, the principal commercial maritime routes have changed little, and the two trans-oceanic passages use the Panama and Suez Canal. Exponential growth in world trade has led to an even higher rate of increase in ship numbers causing congestion and longer waiting times for ships awaiting convoy passage. The economy of scale considerations has resulted in ship sizes, particularly container ships getting much larger in size that the Panama Canal could not handle due to width limitations (32.2 meters) in the locks. The formal opening of a wider third set of locks in June 2016 has facilitated ships up to 49 meters' width gaining access to the Canal (Panama Canal Authority, 2016). The third pair of locks can accommodate container ships with loads up to 13000/14000 TEUs[64] when compared to 5000 TEUs in the existing locks and doubles the capacity of the Panama Canal overall (Panama Canal Authority, 2016). The expansion of the Panama Canal addresses the problem of congestion and size limitation only in the short-medium term, however, and an alternate route is required not only to accommodate bigger ships but more importantly to offer some competition to the existing entities. Ships have already begun using the Northern Sea Route in the last decade (Northern Sea Route Information Office, 2016) and the NWP is projected to be substantially ice free (summer season) by the middle of this century (Smith et al., 2013) to commercial ship transit traffic. This chapter conducts a Cost-Benefit analysis to evaluate the utility of the CAROM in improving such economic modelling and to assess the relative economics of shipping containers through the NWP and the Panama Canal on board ice classed and non-ice class vessels respectively. The methodology adopted is to

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[64] TEU: Twenty-foot equivalent units – the standard size of a shipping container.

calculate the overall costs of operating two sizes of container ships on the Rotterdam to Tokyo route (Figure 27) and determine the 'RFR' per TEU for the two routes. The 'RFR' computation methodology is a variant on the annual cash flow analysis that focuses exclusively on the cost side of the equation and balances with the revenue required to cover the costs (Stopford, 1997). Two Case Studies, one using a hypothetical Panamax size (5000 TEUs) container vessel and the other using a hypothetical Neo-Panamax (10000 TEUs) is conducted. The ice class ship (PC4) selected to transit the NWP is scheduled to be deployed via Panama Canal during the rest of the year and the non-ice class vessel takes the Panama Canal route for the entire year.

5.2.1 Cost Comparison: NWP Vs. Panama Route

The CBA involves a comparison of estimated costs involved in operating a Panamax (PC-4 and OW class) and a Neo-Panamax container vessel (PC-4 and OW class) on the Rotterdam to Tokyo route via the Panama Canal and the Northwest Passage (NWP) simultaneously. The Panamax and Neo-Panamax container ships selected for this purpose include an ice-classed (PC-4) Category 'A' ship and a non-ice (OW) class container ship that transits the Panama Canal between the two ports for the entire year. The ice class container ship is required to transit the NWP in the summer navigation season (4 months) only. Container shipping may prefer the southerly route during the winter months to avoid scheduling uncertainties in the high north. Smith and Stephenson (2013) demonstrated estimates of Arctic marine accessibility (Table 20) this century under various RCP climate forcing scenarios for three separate ship types during the summer navigation season.

This study has assumed four months steaming (120 days) during the Arctic summer for the ice class (PC4) vessel via the NWP and the rest eight months through the Panama Canal. The 'Required Freight Rate' so obtained is compared for two different sizes of ships: Panamax and the Neo Panamax with two separate load factors (60% and 80%) ceteris paribus.

Table 20
Navigation season length-NWP –Spatial averages

PROJECTED-NAVIGATION DAYS-SUMMER (JULY-OCTOBER)						
	NORTH WEST PASSAGE					
	PC3		PC6		Non-Ice Class/OW	
RCP4.5	Navigable Days /SD					
	Days	*SD*	Days	*SD*	Days	*SD*
2011-2030	89	*19*	79	*19*	69	*19*
2045-2065	109	*13*	96	*18*	83	*18*
2080-2099	114	*17*	94	*18*	84	*17*
RCP6.0						
2011-2030	86	*15*	76	*16*	67	*15*
2045-2065	96	*16*	85	*17*	74	*15*
2080-2099	116	*10*	107	*15*	95	*16*
RCP8.5						
2011-2030	84	*16*	75	*15*	66	*13*
2045-2065	121	*4*	115	*8*	105	*12*
2080-2099	122	*1*	120	*4*	116	*6*
RCP	Representative Concentration Pathway- Climate forcing scenario					
SD	Standard	Deviation				
PC3	Polar Class 3					
PC6	Polar Class 6					
OW	Open Water					

Note: Note: Adapted from "Projected 21st-century changes to Arctic marine access" by *Scott R. Stephenson, Laurence C. Smith, Lawson W. Brigham, John A. Agnew, 2013, pp37*

The third set of Panama Canal locks can accommodate the Neo Panamax and so can the Northwest Passage. These vessels may become the new normal for ocean shipping in the future, if one goes by the current trend of mega container ship induction (Rodrigues et al., 2013) to the global container fleet and prudent to investigate as such.

The principal purpose is to test the economy of scale advantage on both routes assuming the NWP transit to be free of charge for the moment, unlike the NSR administration that imposes a significant ice-breaking fee for the passage. The container trade between Asia and Europe suffers from a trade imbalance (UNCTAD, 2015) that affects vessel utilization (load factor) in the various shipping strings (routes) among other factors. Ships with cargo from NE Asia to the West have a much higher utilization rate than the backhaul passage that mostly carries high-value goods and empties from NW Europe. The study has assumed an average 60 % load factor for the NWP route and an 80% average load factor for the Panama Canal route. The vessel utility assumption with respect to the NWP is solely for transit purposes (no intermediate ports to service) and the ship services Tokyo and Rotterdam for the entire year. In the liner-shipping model, the trans-shipment port (intermediate ports to offload containers) is a popular option than the two-port concept assumed in the study. The Arctic region does not have trans-shipment ports currently, hence the assumption. Lack of trans-shipment ports is partly the reason for a reduced load factor compared to the southerly route.

A comprehensive cost analysis is conducted to calculate the Voyage costs, Operation costs and Capital costs based on current data for variables such as bunker fuel, Panama Canal transit charges, and LIBOR[65] rates. The ships used (Table 21) in the CBA are of standard dimensions, and the fuel consumption is interpolated from a Speed-Fuel

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[65] LIBOR: London Interbank Offered Rate

consumption graph for containerships. The average bunker fuel prices (IFO 380 cst[66]) during the last ten years have varied within a US$ 200/MT to US$ 600/MT range in Rotterdam (Appendix 25). The study has used the current bunker prices (US$ 225/MT) and a higher range (US$ 550/MT) to compare the effect on the 'RFR.'

Table 21

Ship Data- Control Table

Dimensions	Panamax		NeoPanamax
Length	294	Mtrs	360
Breadth	32	Mtrs	46
Draft	12	Mtrs	15
Engine Rating	40	KW	93
Max rated speed	24	Kts	24
Economical Spd	**21**	**Kts**	**21**
Average Speed -Ice	**11**	**Kts**	**11**
Fuel Cons	**80**	**MT/day**	**200**
Fuel Price	**225**	**MT/Ton**	**225**
Total TEU Capacity	5000	TEU	10000
Av.Load factor(60%)	**3000**	**TEU**	**6000**
Panama Canal Toll	**60**	**US$/TEU**	**50**
NWP-Ice Transit Fees	0	US$	0

Note: Data for Neo Panamax container vessel from Argo Engineering and Design "*Design of a Dual-Fueled, New-Panamax Containership*" by Max Caballero, David Carrier, Jack Hamel, and Lexie Ludewig.

The hypothetical Neo-Panamax ship has a full load draft of 15 meters and can safely transit the NWP as well as the new set of locks in the Panama Canal.

5.2.2.1 CBA-1: Panamax Container Ship

We calculate the annual cost accrued in operating an ice class Panamax vessel with an assumed load factor of 60% (4 months) and 80% (8 months) to a non-ice class ship

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[66] IFO 380cst: Grade of fuel most commonly used on ships

making all the voyages through the Panama Canal with a standard load factor of 80%. The load factor is increased to 80% subsequently for the ice class ship to gain parity with the non-ice class ship and the economic viability ascertained. The freight rate (US$/TEU) that equalizes the cost/TEU is the ‘RFR’ that a ship owner must aim for to achieve economic parity. The trade imbalance is accounted for in the load factor for both the east bound and west bound trips.

Table 22

Comparison: ‘Required Freight Rate’-Panamax Vessel Load Factors

Panamax(5000 TEU's)			
Route	Load	Fuel Price	
NWP	**60%**	$225/MT	
Panama	80%		
Annual Performance			
		Via Panama	
		12 M	NWP+Panama
Voyage Cost		$9,431,630	$8,471,612
Operating Cost		$2,232,000	$2,943,600
Capital Cost		$5,415,696	$6,974,946
TEU's		51320	52200
Annual Cost (US$)		$17,079,326	$18,390,158
RFR	**TEU/US$**	**$333**	**$352**

Panamax(5000 TEU's)			
Route	Load	Fuel Price	
NWP	**80%**	$225/MT	
Panama	**80%**		
Annual Performance			
		Via Panama	
		12M	NWP+Panama
Voyage Cost		$9,431,630	$8,471,612
Operating Cost		$2,232,000	$2,943,600
Capital Cost		$5,415,696	$6,974,696
TEU's		51320	58520
Annual Cost (US$)		$17,079,326	$18,389,908
RFR	**TEU/US$**	**$333**	**$314**

Source: Author

The Voyage Cost category primarily accounts for the bunker fuel costs and the Panama Canal tariffs. Bunker fuel costs account for 45% to 50% (Rodrigues et al., 2013) of the expenditure budget, by far the largest share. The fuel prices are highly volatile, not controlled by the ship-owner and vary worldwide even daily. The study has incorporated the current bunker prices (Athenian Shipbrokers, 2016) prevailing at Rotterdam ($225/MT), the rates being cheaper than a Tokyo bunker stem. The Panama Canal tariff is dictated by the Panama Canal Authority (Appendix 26) and outside the ship owner’s remit as well. The NWP transit fees are assumed to be nil for the Canadian Arctic. The Operating Costs account for crew wages, insurance (H&M[67], P& I[68]), regular repair and maintenance and the administration costs. The Hull and Machinery premium for the NWP segment is unknown since there is no empirical data available for the icebound route but assumed 80% higher than the Panama Canal route; the P&I premium is estimated to be 30% dearer for the NWP passage. The rates reflect the risk perceived by the Marine Insurance industry on a largely uncharted route with no ports or ship repair facilities to resort to in case of contingencies. The perception and the premium may normalize as more ships transit the NWP in tandem with a gradual improvement in infrastructure in the coming decades and adequate risk mitigation measures in ship operation. The Capital costs account for the financing cost of the ships. The debt to equity ratio assumed 70% to 30% with a seven-year term and the prevailing LIBOR rates (12 monthly) at 1.25%. The loan profile is built with a lending margin of 2% and a balloon payout in the end. The shipbuilding costs for both the Panamax and the Neo-Panamax ship reflect the latest price trend (Appendix 27) in East Asian shipyards. The Panamax estimated to cost US$ 47 million and the Neo-Panamax valued at US$ 90 million with the ice class variants billed 30% higher respectively, a modest assumption for the ice class variant and could be higher. The shipbuilding rates have been depressed considerably in recent times following vessel overcapacity primarily in the container ship segment (Clarkson, 2016) and the vessels used in the CBA reflect those statistics.

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[67] H&M: Hull and Machinery

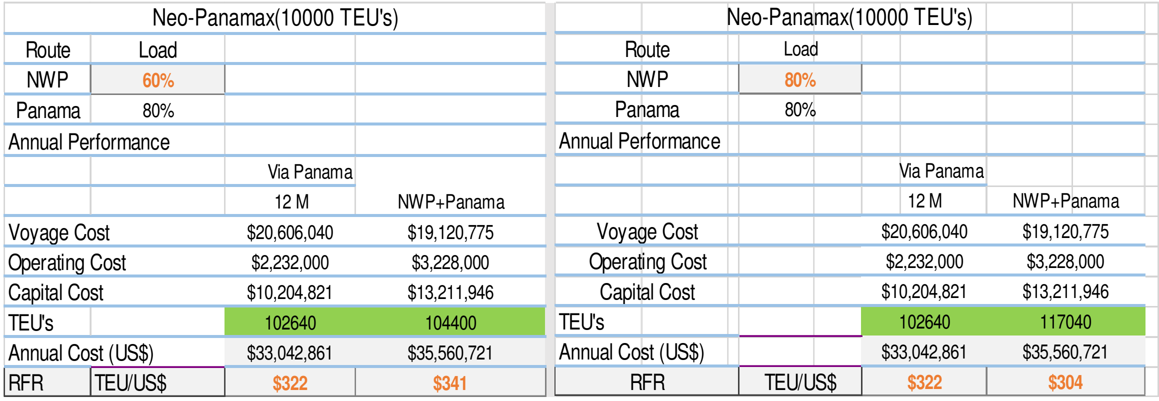
[68] P&I: Protection and Indemnity

The total number of containers (dry type) transported for the year on each route is converted in TEUs for ease of calculation since there can be a mix of at least two different standard box sizes (20 feet and 40 feet length) if not more. The numbers arrived from the average load factor per trip is added for all the trips to get at the total volume transported (TEUs) per ship. The ‘RFR’ is the revenue/TEU that the vessel needs to earn to cover the costs and is the ratio of the consolidated costs and the annual volume transported. The Panamax RFR (Table 22) indicates the extreme sensitivity that the load factor can cause to the economic viability of the Northwest Passage. The NWP seems marginally preferable to the Panama route if the load factor is increased to 80% as it turns out a lower ‘RFR’ ($314/TEU) in the backdrop of a fixed period of transit assumed to be four months. Economic viability improves further if the length of transit exceeds beyond four months and that would depend on the rate and extent of receding ice. With a 60% load factor and a 4-month NWP transit, the route is clearly unviable, an 80% load factor does indicate mathematical viability but may be in the margin of error as far as assumptions go and hence not a clinching commercial argument.

5.2.2.2 CBA-2: Neo Panamax Vessel Comparison of 'RFR'

The Neo-Panamax vessel is tested the same way, the difference being this is equivalent to two Panamax vessels carrying a consolidated load on one ship. The study wishes to test if large container ships will bring a tangible economy of scale advantage to the NWP. A Neo-Panamax ship may cost almost the same crew staffing and administration costs as a single Panamax ship transporting twice the load, but the new-building and fuel consumption budget with the current empirical data does not result in any significant savings.

Table 23
Comparison: 'Required Freight Rate': Neo-Panamax Load Factors



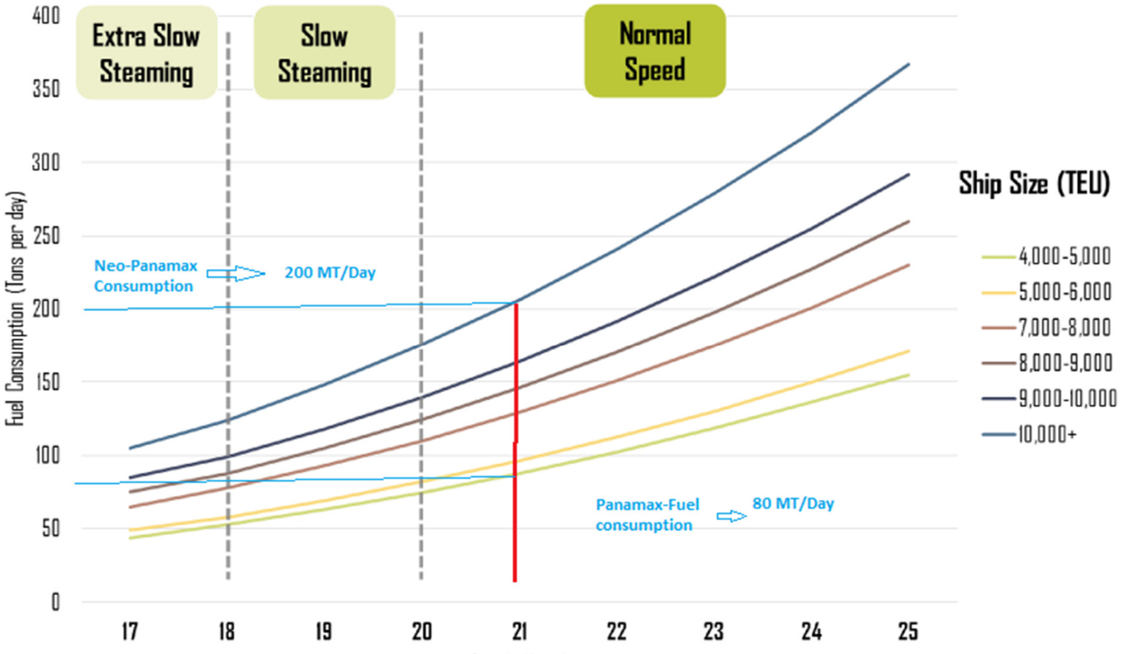
Neo-Panamax(10000 TEU's)			
Route	Load		
NWP	60%		
Panama	80%		
Annual Performance			
		Via Panama	
		12 M	NWP+Panama
Voyage Cost		$20,606,040	$19,120,775
Operating Cost		$2,232,000	$3,228,000
Capital Cost		$10,204,821	$13,211,946
TEU's		102640	104400
Annual Cost (US$)		$33,042,861	$35,560,721
RFR	TEU/US$	$322	$341

Neo-Panamax(10000 TEU's)			
Route	Load		
NWP	80%		
Panama	80%		
Annual Performance			
		Via Panama	
		12 M	NWP+Panama
Voyage Cost		$20,606,040	$19,120,775
Operating Cost		$2,232,000	$3,228,000
Capital Cost		$10,204,821	$13,211,946
TEU's		102640	117040
Annual Cost (US$)		$33,042,861	$35,560,721
RFR	TEU/US$	$322	$304

Source: Author

The Neo-Panamax RFR is marginally better ($ 304/TEU) than the Panamax estimates at 80% load factor (Table 23) but not a convincing case considering the high capital costs in building and operating such a ship on a two-port rotation. Moreover, an 80% load factor equates to a huge volume of containers without trans-shipment possibilities.

A comparative analysis of the two ship sizes and types indicate the annual costs for the Neo-Panamax vessel equate to about 96% of the cost of operating two Panamax vessels independently. New generation Dual fuel (Diesel and LNG powered) large container vessels may result in more fuel-saving engine technology in the future that could reduce the costs further. The increase in the load factor to 80% does make the NWP more suitable for the Neo-Panamax size as well. The fuel consumption at an average speed of 21 knots interpolated from the consumption Vs. Speed graph (Figure 28) is 2.5 times higher for a vessel twice the size. The costs will further amplify as the bunker fuel prices increase from the current low prices incorporated in the CBA (section 5.2). It may be interesting to assess the economic viability when the fuel prices are high (US$ 550/MT).



Adapted from-Rodrigue, J-P et al. (2013)

Figure 28: *Fuel consumption Vs. Container ship speed*

Source: Adapted from Rodrigue, J-P, et al., (2013)

Bunker fuel prices, a highly elastic factor but an inelastic commodity in maritime transport mirrors the global crude price fluctuations and forms the largest share of the operating costs. The study has considered the sensitivity of the bunker fuel costs on the NWP transit keeping the load factor at 80% (Table 24). A low fuel price (US$225/MT), translates into an 'RFR' share of 94% for the NWP compared to the Panama Canal rate. A high fuel price (US$ 550M/T), returns a 93% 'RFR' for the NWP signifying it is preferable to consider the NWP as fuel prices move higher.

Table 24

Economic Viability-NWP Route: Fuel Prices Vs. Vessel Size

Panamax Size				
Load Factor	Fuel Price	RFR ($/Teu)		RFR %age
	$/Ton	PC	NWP	
80%	**225**	**333**	**314**	**94%**
	550	**503**	**466**	**93%**
Neo-Panamax Size				
Load Factor	Fuel Price	RFR ($/Teu)		RFR %age
	$/Ton	PC	NWP	
80%	**225**	**322**	**304**	**94%**
	550	**535**	**493**	**92%**
Transit				
PC	Panama	Canal	All Year	
NWP	NWP(4M)	Canal	8M	

Source: Author

The situation in favour of an NWP transit gets better with increasing vessel size and higher bunker fuel prices as the lower 'RFR' percentages demonstrate. No transit fee is applied in the calculations for the NWP, but an imposition of a transit levy on similar lines as the Northern Sea Route Administration in future may negate the slender cost differential in favour of the NWP, making it unviable. One may have to wait for an extended navigation season beyond the assumed four months to reap the benefits of the NWP, and that depends on how fast the sea ice recedes in future.

Chapter 6: Conclusions

6.1 Summary

The interdisciplinary approach of research pursued in this study allowed synthesis of ideas and expertise from nautical science, engineering, and economics to connect via Geographic Information Systems. A maritime route transportation model in ArcGIS was developed with currently available datasets (nautical and ice climatology) and several limitations including charting, hydrography, spatial resolution and sea-ice thickness measurements among others. A rapid decline in Arctic sea ice and reports of emerging transport routes through the erstwhile frozen seas provided the impetus for this study. Emerging shipping routes in the NWP provided the challenge to marshal all the resources available to develop a workable maritime route model using GI systems. The study has addressed six fundamental research questions to achieve its stated objectives. The preparatory work was done that lead to the proposal identified an interdisciplinary approach in GIS to conduct maritime route network modelling. Several instances of route optimization in other modes of transport involving spatial planning and route determination already exist in the ArcGIS suite. The two pillars essential for digital mapping, spatial analysis and route optimization in the maritime domain are the nautical and sea-ice datasets in vector format. A literature review of CIS and NIC sea-ice charts identified ESRI's ArcGIS as the GI system of convenience that the prototype model 'CAROM' could use because of its analytical and network solution capabilities. ESRI's software is also associated with the production of digital charts including the DCW since

1993 and as such draw upon a long experience in sea-ice chart production and analysis. Electronic Navigation Charts (vector format) produced by CHS is well supported in ArcGIS through the S-57 ESRI Viewer add-on that answered the first research question.

CHS publishes Electronic Navigation Charts of the Northwest Passage compatible with ArcGIS. The digital data standard of the IHO (S-57) is the data protocol required to transfer Electronic Navigation Charts to the non-navigational ‘ArcMap’ environment for spatial analysis. The S-57 ENCs form the base layer for route plotting and route network creation. ESRI’s ‘S-57 Viewer’ facilitates the ENC transfer process. CIS publishes ice datasets for the Canadian Arctic in the SIGRID-3 (vector) format compatible with ArcGIS. CIS also uses the same software to produce their ice analysis charts. Thus, the two most essential elements required to build the model are available in a compatible format (vector) and supported by the ArcGIS suite. A complete digital maritime route network is a prerequisite to conducting spatial analysis and geoprocessing. Currently, CHS does not provide full ENC coverage of the NWP but they do publish paper-based charts. The routes plotted on the paper charts (non-ENC areas) were buffered on either side to check for safe water in relation to draft and other charted dangers and transferred to ArcMap. A feature class was created to join the transferred routes to the existing network on the ENCs thereby completing the digital maritime network in the NWP. The CIS ice datasets, although available on a weekly basis imported in ‘ArcMap’ thereby completing the requirements of the “Network Analyst’ to devise a workable model. The speed in sea-ice is essential to estimate a transit time in ice-bound routes such as the NWP that the Ship Transit-in-ice Model can predict in various ice regimes. The attribute tables in the CIS ice datasets enable calculation of ice thickness necessary for the purpose with a certain degree of approximation due to the ‘missing’ or indeterminate values which, introduces an uncertainty in ice thickness averaging that the model has not accounted for.

While the navigational data provides the ‘Safe Navigation Zone’ as a base layer contributing to route safety, the Ship-Transit Model contributes with speed through various ice regimes essential to model the hierarchy network with sea-ice impedance. The two together complete the elements that the CAROM requires to calculate the ‘least cost’ path for a certain ice dataset. The validation and simulation case studies in chapter 4 have proved the utility of the CAROM in predicting the waypoints a ship should follow to navigate the path of least resistance.

The study demonstrated that the proposed model must be able to contribute operationally and tactically to the end user, the navigator on board. The ice navigator needs the waypoints when confronted with sea ice and all the challenges, the Northwest Passage embodies. The route model output is essentially a set of waypoints depicting the ‘least cost’ path for the vessel to traverse. The waypoints are a set of geographical coordinates can be plotted instantly either on the ECDIS or the nautical paper charts for voyage planning purposes while the vessel is underway. Distance and speed-in-ice are the two other parameters required to predict the transit time in the NWP segment that contributes in computing the entire trans-Arctic route for the final economic analysis. While the Mariner on board may be the biggest beneficiary of the CAROM tool, other stakeholders such as ship operators, port authorities, insurance companies, and Govt. agencies may benefit from the information provided. The CAROM is a good first step towards risk mitigation and decision making in ice. It is, however, not intended to replace the judgment of the Shipmaster.

The comparative economic analysis may help shipping companies in vessel deployment, planning, and positioning of containers. The liner shipping trade (containerized cargo) is geared towards the provision of regular services between specified ports, as per fixed timetables and prices advertised well in advance (Haralambides, 2007). A major cost element that liner shipping companies deal with is the global positioning of empty containers to be stuffed and loaded onboard their ships while calling ports. The positioning of containers will be a good logistical exercise for a shipping company deciding to opt for trans-shipment along the NWP route and can only happen with container port infrastructure in place along the Arctic route. Until such time, an end-end two-port option is the only practical solution as assumed in the Cost-Benefit analysis. Chapter 5 has dealt extensively with the economic viability aspect analyzing the various scenarios with a 4-month navigation period through the NWP using ice class (PC-4) hypothetical container ships of the Panamax (5000 TEUs) and Neo-Panamax (10000 TEUs) capacity. Calculations point to the economic unviability of a trans-Arctic route in comparison to the Panama Canal. Due to lack of empirical data, several assumptions were made pertaining to load factor, fuel consumption (open water and ice covered passage) and a no tariff scenario (NWP). Economy of scale considerations were also tested by doubling the number of container carried (Neo-Panamax vessel) and subjecting the economic model to two different fuel price bands (low and high fuel scenario). The RFR (USD/TEU) is marginally better with an 80% load factor, high fuel price and bigger ship size in favour of the NWP but not good enough for a commercial ship operator to divert a vessel from the Panama Canal. A navigation season longer than 4-months is required coupled with trans-shipment ports for trans-Arctic shipping to be a commercial reality.

This study applied a practical approach to maritime route modelling in GIS using data sources (sea-ice charts) and ENCs that the ships use for navigation, helped by the interdisciplinary convergence of thoughts and expertise as enlisted (Table 25):

Table 25
New concepts applied in route modelling

Concept	**Utility**
MCDA-SDSS	Create Safe Navigation Zone relative to ship's draft
Safe Water Zone (SNZ)-Chart Layer	Create a safe zone of water relative to depth, ship's draft and charted dangers, cautionary areas
Ice Concentration Categories	Parsing ice polygons to calculate Ice Numerals/Risk Index Outcomes
Ice thickness - Partial concentration Categories	Input- Ship transit-in-ice model
Ship Speed in Ice Regimes-Concentration and Thickness	Input- Network Analyst. Ice impedance hierarchy table
Computer-Aided Arctic Route Optimization Model (CAROM)	Voyage planning and tactical navigation in ice
	Distance traversed,time of transit in ice
Cost-Benefit Analysis	CAROM outputs
Neo-Panamax container vessel	Comparative cost evaluation

Source: Author

6.2 Limitations/Challenges

Maritime transportation in the Arctic could only begin with a sustained reduction in Arctic Sea-ice thickness and extent over the last few decades. It had been a frozen sea for centuries and thus deficient in maritime infrastructure besides the unique challenges of high latitude navigation. The receding sea-ice presents unique opportunities for commercial activities that trigger the need for increased shipping activities. Although shipping activities in the Canadian Arctic is low compared to the southern waters and the Russian Arctic, it is estimated that mining projects in the eastern Arctic alone will double the traffic by 2020 (Govt. of Canada-A, 2016). Population growth in northern communities, an increase in Arctic cruise tourism and the receding ice will bring in more ships to an area that is not adequately charted and surveyed. The current state of infrastructure such as ports, ship repair facilities, ports of refuge and aids to navigation in the Canadian Arctic is clearly inadequate to the impending rise in commercial ship traffic. Lack of icebreaking capacity and challenges in sea- ice data acquisition due to lack of satellites will directly affect the safety of ships that is projected to double and carries a perceived risk of ship-sourced pollution. The absence of Ice Service Specialists on board the Canadian Coast Guard ships as of 2014 is another limitation in the provision of ice services at a time when shipping activities are on the rise. Satellite surveillance in detecting oil spills due to increased shipping activity is a priority that goes hand in hand alongside sea-ice data acquisition with SAR imagery. The current shortage of satellite surveillance capabilities has resulted in reduced sea-ice detection capability. Spatial resolution and sea-ice thickness can be suitably incorporated in a geospatial model but the available datasets have limitations currently that affect quality of source data inputs in the CAROM as well as the Ship-Transit-in-ice Model.

Evolving technology will certainly improve this aspect with the provision of adequate space assets such as satellites focused on the Canadian Arctic and used for sea-ice data acquisition purposes only. Reporting of ridged ice data will certainly help in calculating resistive forces even better and data on ice pressure, and drift would add to the better speed predictions in ice. Sea and swell data overlay would have made modelling and speed predictions that much better. The Route Optimization Model presented in the study is a preliminary first step and bears testimony to the limitations experienced in the development phase, but we did manage to sail through the sea-ice. This interdisciplinary study required informed assumptions be made drawing upon author's experience, inputs from Arctic experts, sea-ice and navigational data available in the public domain.

6.3 Future Research Opportunities

The model developed and exhibited has an extremely powerful aspect that lies in its digital scope with enormous expansion possibilities in future research work. CAROM in its present configuration is not constrained by volume of data inputs to include several environmental and ice climatology parameters added in ArcGIS, or any other compatible GIS suite provided the data be usable and readily available. Environment variables such as current, wind, ice- pressure, and drift may subsequently be included for spatial analysis to achieve better optimization results. High-quality ice climatological data and advanced versions of the uniform coding format (SIGRID-3) expected in the future may include data on ridged ice and, eliminate missing variables and undetermined sea-ice parameters leading to better ice impedance factors. The CAROM is adaptable to any part of the world, even in open oceans, rivers, and lakes. Evolving technology and acquisition of sea-ice data in ‘real time’ may transform the voyage plan from a static to dynamic mode but further research is required to test the practical usage of data streaming on a slow moving entity such as a ship. Several IMO initiatives including the e-navigation Strategic Implementation Plan (2015-2019) point towards the tremendous advantage the digital platform occupies in the global maritime strategy. The proposed route model may serve as a useful element in IMO’s e-navigation vision. The CAROM embedded in shipboard navigation equipment such as an ECDIS to assist in instant decision-making is a possibility requiring further research.

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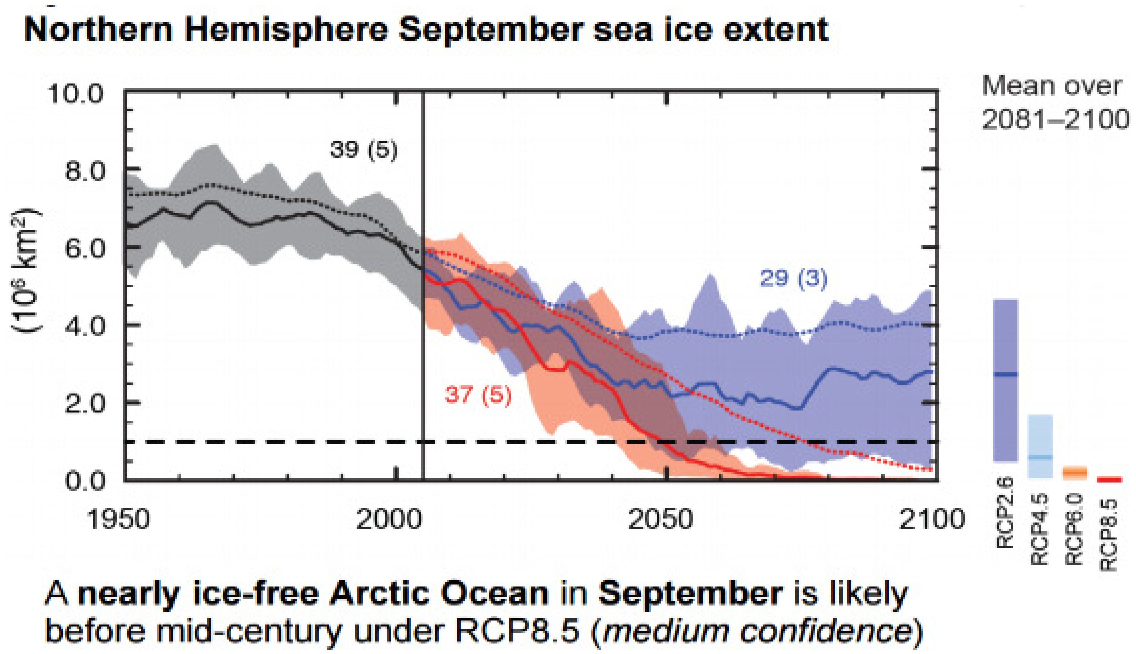
Appendices

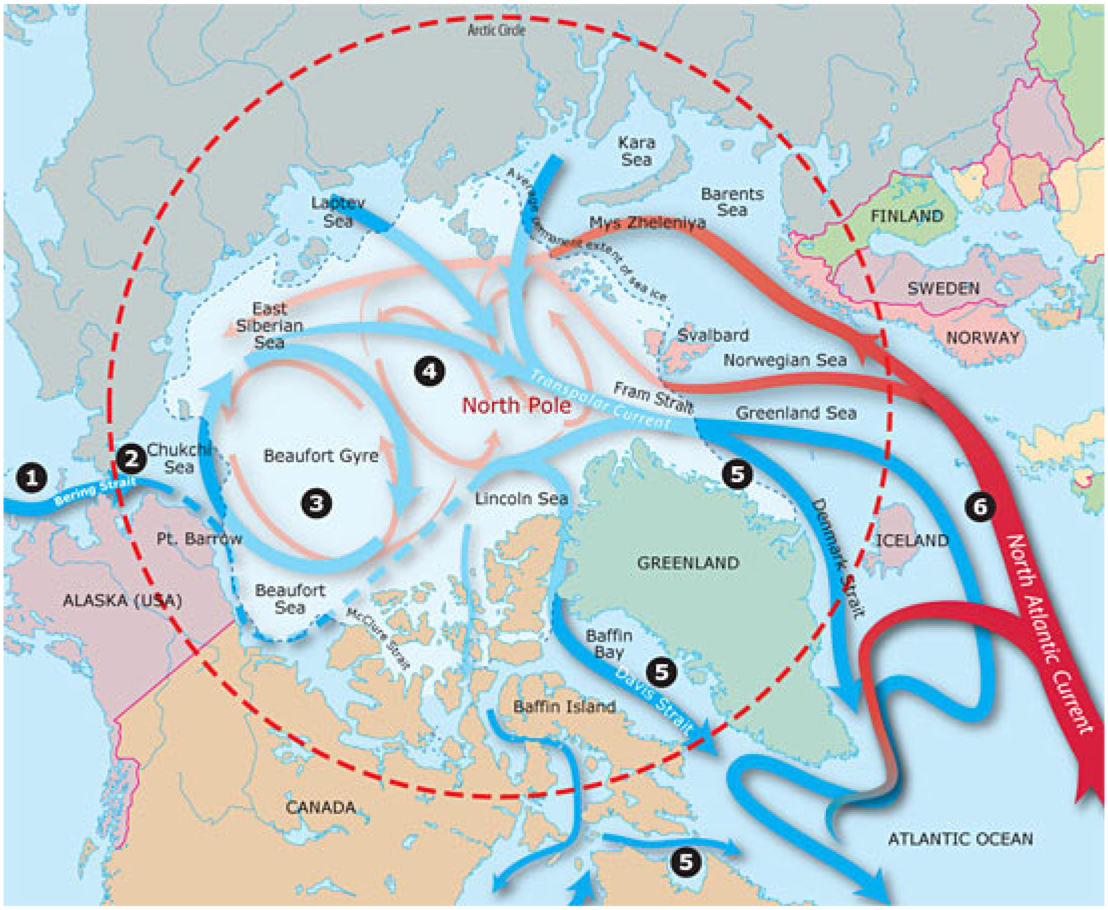
Appendix 1: September Sea Ice Extent-Northern Hemisphere



Source: From (Pachauri & Meyer, 2015), retrieved February 14, 2016 from

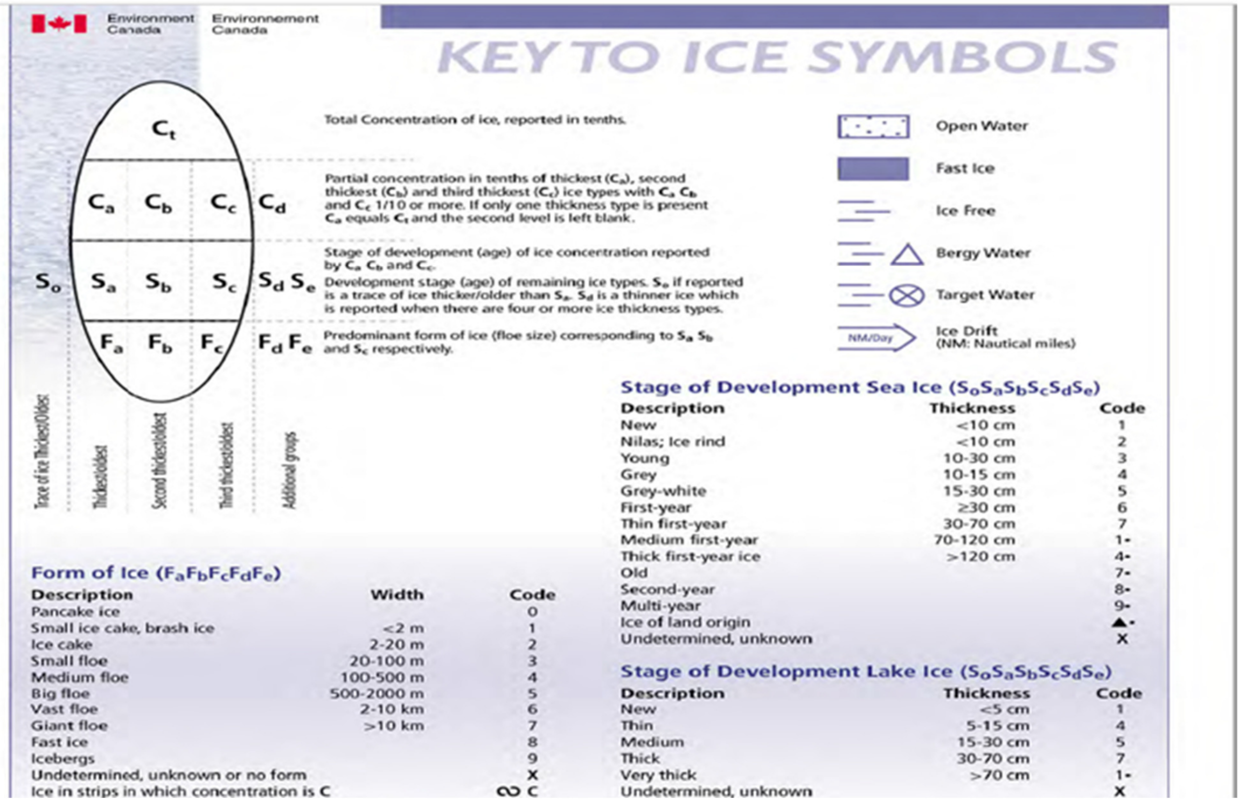
https://www.ipcc.ch/report/ar5/syr/

Appendix 2: Arctic Ocean Currents and circulation



Source: Polar Data Maps. Retrieved July 1, 2016, from http://90-north.com/resources/polar-data-maps/

Appendix 3: WMO Sea Ice: Egg Code and Terminology



KEY TO ICE SYMBOLS

Total Concentration of ice, reported in tenths.

Partial concentration in tenths of thickest (C_a), second thickest (C_b) and third thickest (C_c) ice types with C_a C_b and C_c 1/10 or more. If only one thickness type is present C_a equals C_t and the second level is left blank.

Stage of development (age) of ice concentration reported by C_a C_b and C_c.

Development stage (age) of remaining ice types. S_o if reported is a trace of ice thicker/older than S_a. S_d is a thinner ice which is reported when there are four or more ice thickness types.

Predominant form of ice (floe size) corresponding to S_a S_b and S_c respectively.

Open Water
Fast Ice
Ice Free
Bergy Water
Target Water
Ice Drift (NM: Nautical miles)

Stage of Development Sea Ice ($S_oS_aS_bS_cS_dS_e$)

Description	Thickness	Code
New	<10 cm	1
Nilas; Ice rind	<10 cm	2
Young	10-30 cm	3
Grey	10-15 cm	4
Grey-white	15-30 cm	5
First-year	≥30 cm	6
Thin first-year	30-70 cm	7
Medium first-year	70-120 cm	1•
Thick first-year ice	>120 cm	4•
Old		7•
Second-year		8•
Multi-year		9•
Ice of land origin		▲•
Undetermined, unknown		X

Form of Ice ($F_aF_bF_cF_dF_e$)

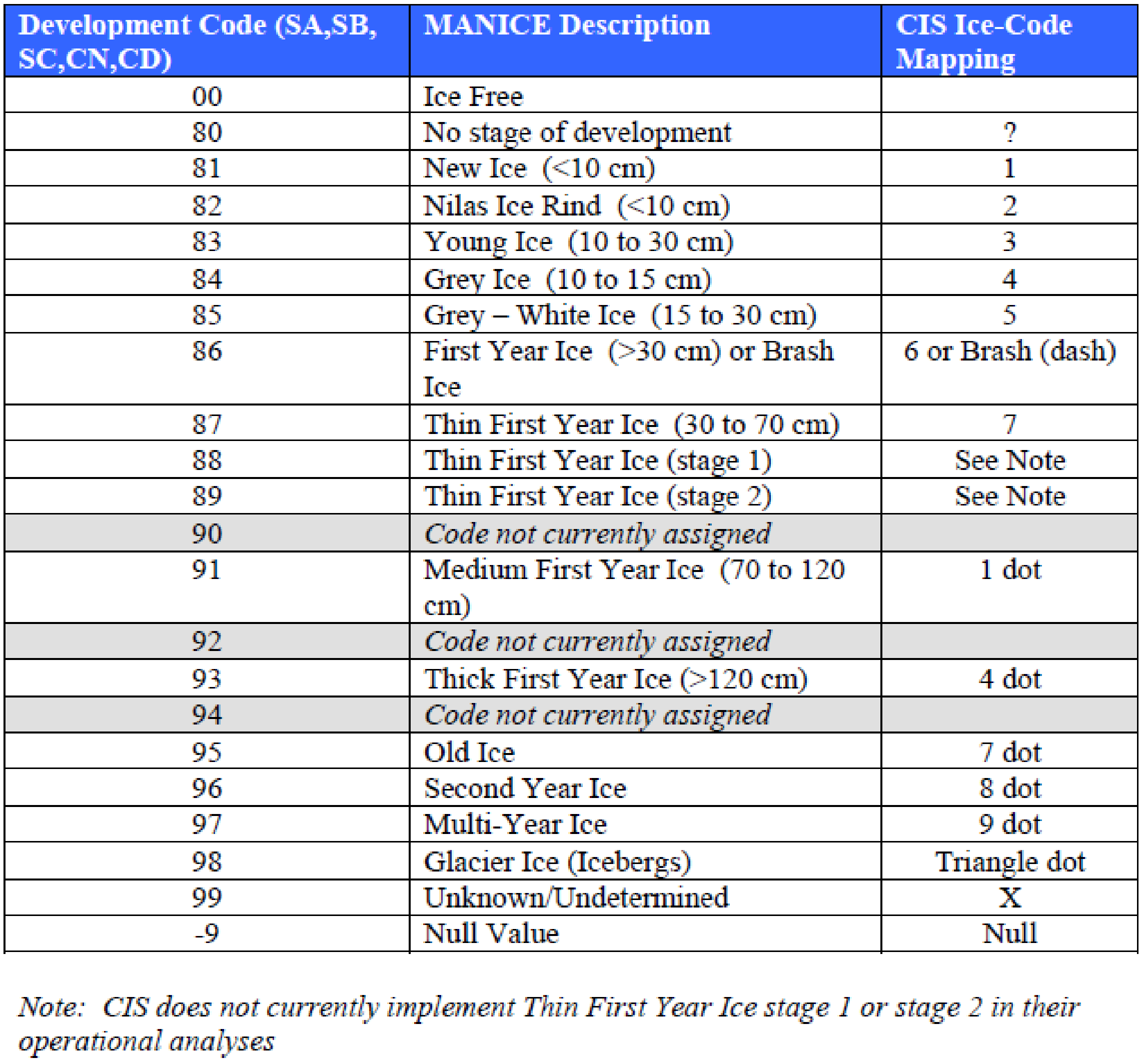
Description	Width	Code
Pancake ice		0
Small ice cake, brash ice	<2 m	1
Ice cake	2-20 m	2
Small floe	20-100 m	3
Medium floe	100-500 m	4
Big floe	500-2000 m	5
Vast floe	2-10 km	6
Giant floe	>10 km	7
Fast ice		8
Icebergs		9
Undetermined, unknown or no form		X
Ice in strips in which concentration is C		∞ C

Stage of Development Lake Ice ($S_oS_aS_bS_cS_dS_e$)

Description	Thickness	Code
New	<5 cm	1
Thin	5-15 cm	4
Medium	15-30 cm	5
Thick	30-70 cm	7
Very thick	>70 cm	1•
Undetermined, unknown		X

Source: From (Environment and Climate Change Canada-D, 2016), retrieved from https://ec.gc.ca/glaces-ice/default.asp?lang=En&n=2CE448E2-1. March 23, 2016.

Appendix 4: SIGRID-3 Schema: Development Codes

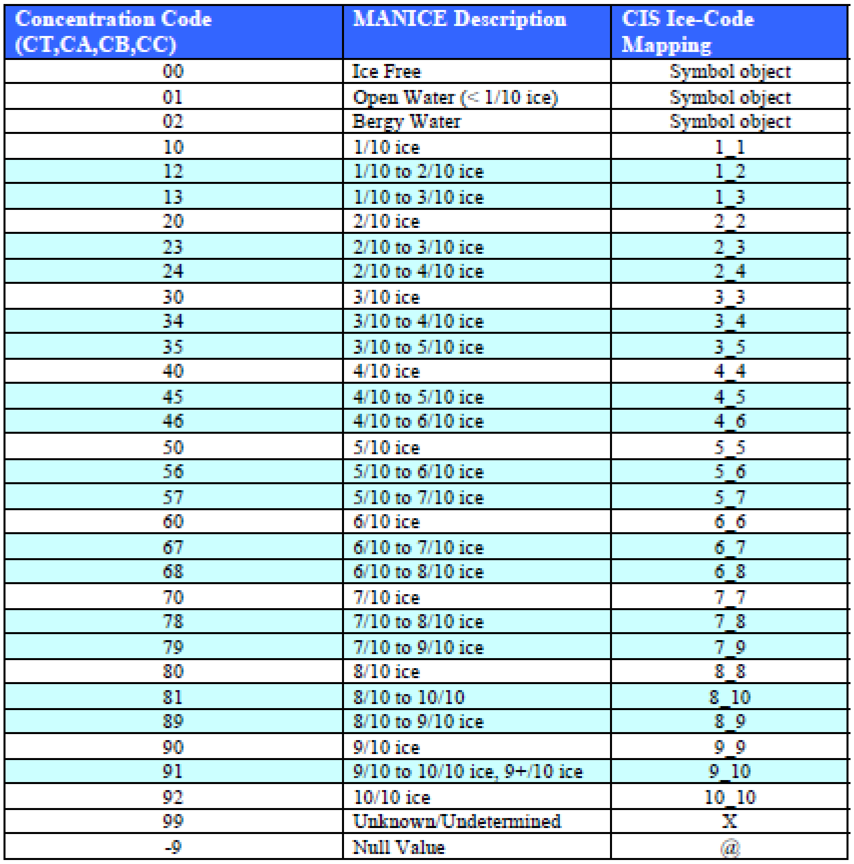


Development Code (SA,SB, SC,CN,CD)	MANICE Description	CIS Ice-Code Mapping
00	Ice Free	
80	No stage of development	?
81	New Ice (<10 cm)	1
82	Nilas Ice Rind (<10 cm)	2
83	Young Ice (10 to 30 cm)	3
84	Grey Ice (10 to 15 cm)	4
85	Grey – White Ice (15 to 30 cm)	5
86	First Year Ice (>30 cm) or Brash Ice	6 or Brash (dash)
87	Thin First Year Ice (30 to 70 cm)	7
88	Thin First Year Ice (stage 1)	See Note
89	Thin First Year Ice (stage 2)	See Note
90	*Code not currently assigned*	
91	Medium First Year Ice (70 to 120 cm)	1 dot
92	*Code not currently assigned*	
93	Thick First Year Ice (>120 cm)	4 dot
94	*Code not currently assigned*	
95	Old Ice	7 dot
96	Second Year Ice	8 dot
97	Multi-Year Ice	9 dot
98	Glacier Ice (Icebergs)	Triangle dot
99	Unknown/Undetermined	X
-9	Null Value	Null

Note: CIS does not currently implement Thin First Year Ice stage 1 or stage 2 in their operational analyses

Source: Environment Canada: Canadian Ice Service SIGRID-3 Implementation 2006, Stage of Development codes for SIGRID-3, pp.8.

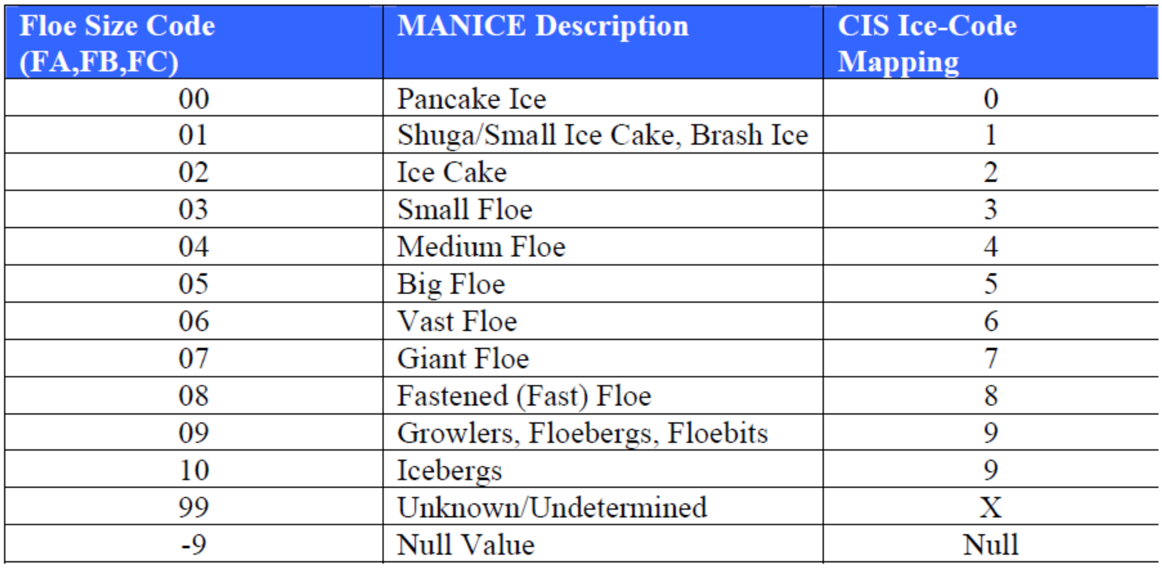
Appendix 5: SIGRID-3 Codes: Ice Concentration



Concentration Code (CT,CA,CB,CC)	MANICE Description	CIS Ice-Code Mapping
00	Ice Free	Symbol object
01	Open Water (< 1/10 ice)	Symbol object
02	Bergy Water	Symbol object
10	1/10 ice	1_1
12	1/10 to 2/10 ice	1_2
13	1/10 to 3/10 ice	1_3
20	2/10 ice	2_2
23	2/10 to 3/10 ice	2_3
24	2/10 to 4/10 ice	2_4
30	3/10 ice	3_3
34	3/10 to 4/10 ice	3_4
35	3/10 to 5/10 ice	3_5
40	4/10 ice	4_4
45	4/10 to 5/10 ice	4_5
46	4/10 to 6/10 ice	4_6
50	5/10 ice	5_5
56	5/10 to 6/10 ice	5_6
57	5/10 to 7/10 ice	5_7
60	6/10 ice	6_6
67	6/10 to 7/10 ice	6_7
68	6/10 to 8/10 ice	6_8
70	7/10 ice	7_7
78	7/10 to 8/10 ice	7_8
79	7/10 to 9/10 ice	7_9
80	8/10 ice	8_8
81	8/10 to 10/10	8_10
89	8/10 to 9/10 ice	8_9
90	9/10 ice	9_9
91	9/10 to 10/10 ice, 9+/10 ice	9_10
92	10/10 ice	10_10
99	Unknown/Undetermined	X
-9	Null Value	@

Source: Environment Canada: *Canadian Ice Service SIGRID-3 Implementation 2006, Concentration codes for SIGRID-3, pp.7.*

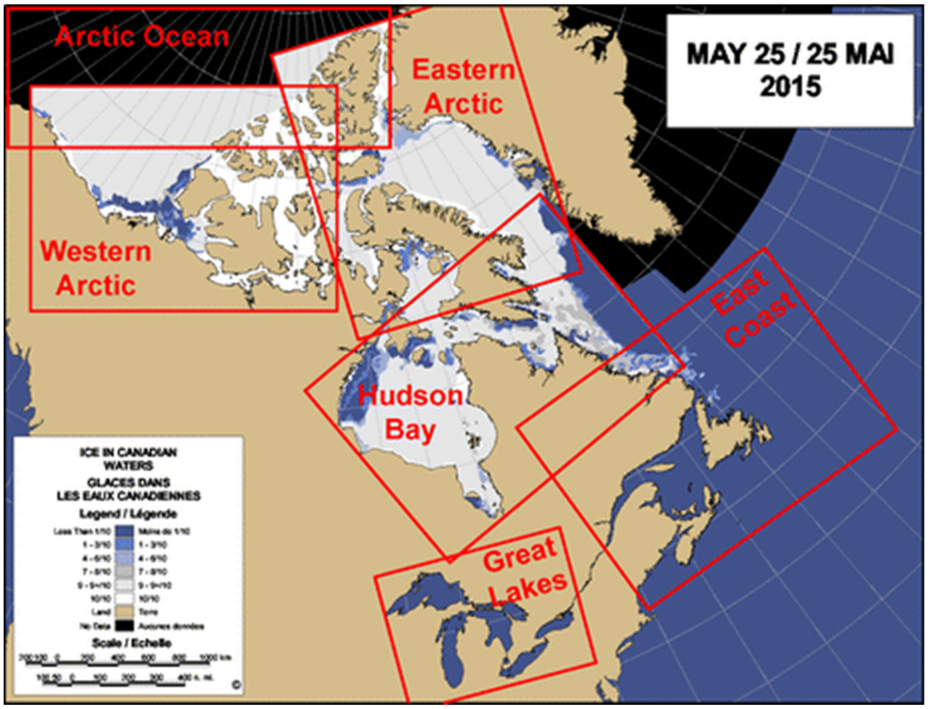
Appendix 6: SIGRID-3 Codes: Floe Size



Floe Size Code (FA,FB,FC)	MANICE Description	CIS Ice-Code Mapping
00	Pancake Ice	0
01	Shuga/Small Ice Cake, Brash Ice	1
02	Ice Cake	2
03	Small Floe	3
04	Medium Floe	4
05	Big Floe	5
06	Vast Floe	6
07	Giant Floe	7
08	Fastened (Fast) Floe	8
09	Growlers, Floebergs, Floebits	9
10	Icebergs	9
99	Unknown/Undetermined	X
-9	Null Value	Null

Source: Environment Canada: *Canadian Ice Service SIGRID-3 Implementation 2006, Floe –size codes for SIGRID-3, pp.9.*

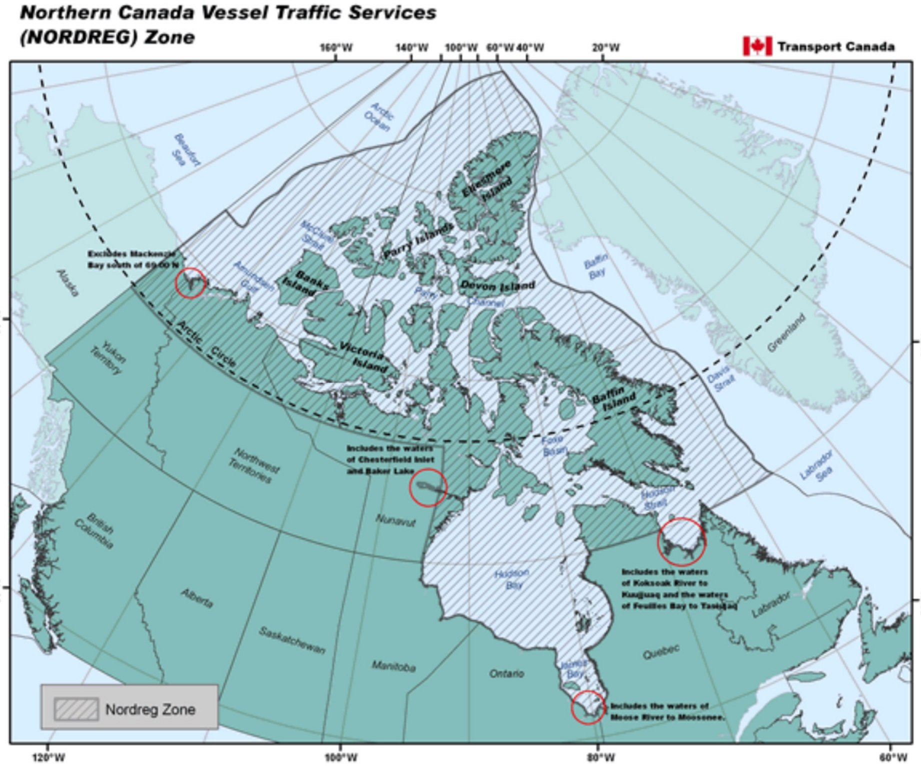
Appendix 7: Ice Chart Coverage Regions: Canadian Ice Service



Source: From (Environment and Climate Change Canada-B, 2016), retrieved July 7, 2016, from

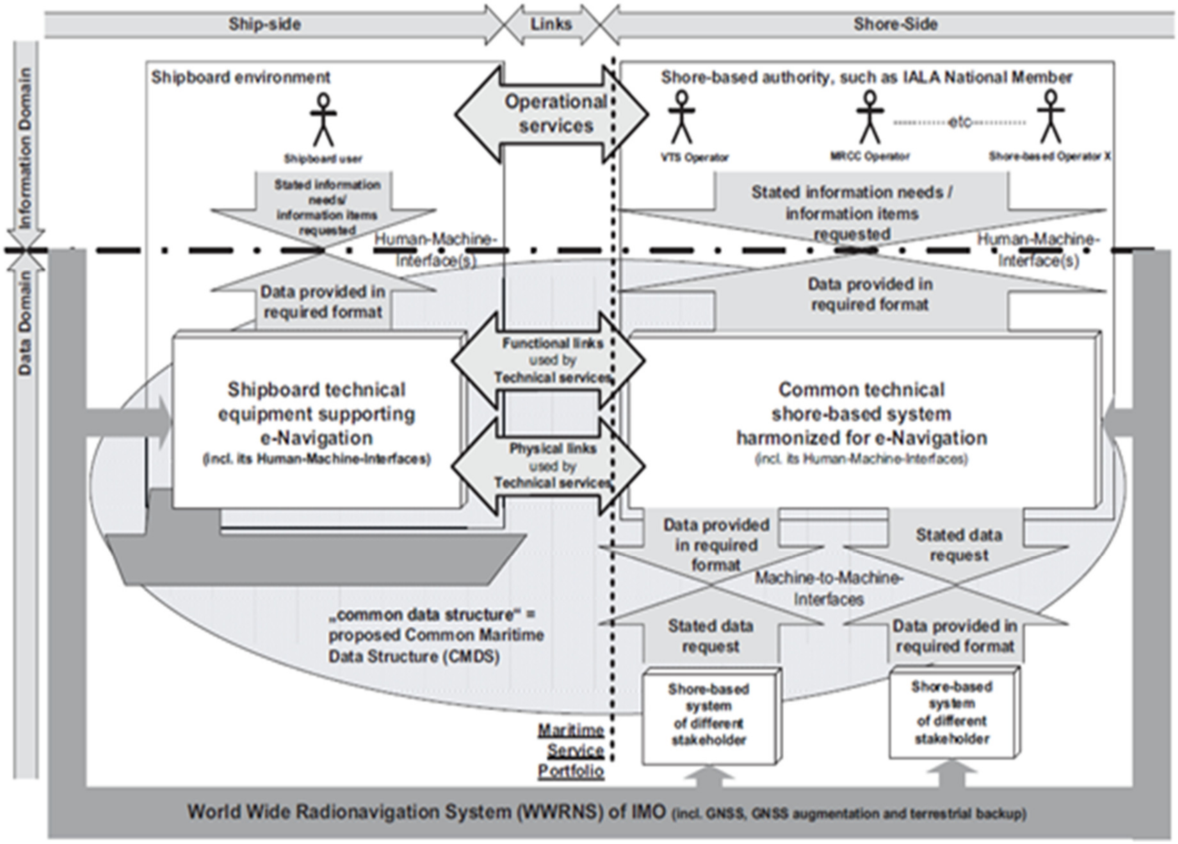
https://www.ec.gc.ca/glaces-ice/,

Appendix 8: Northern Canada Vessel Traffic Services Zone



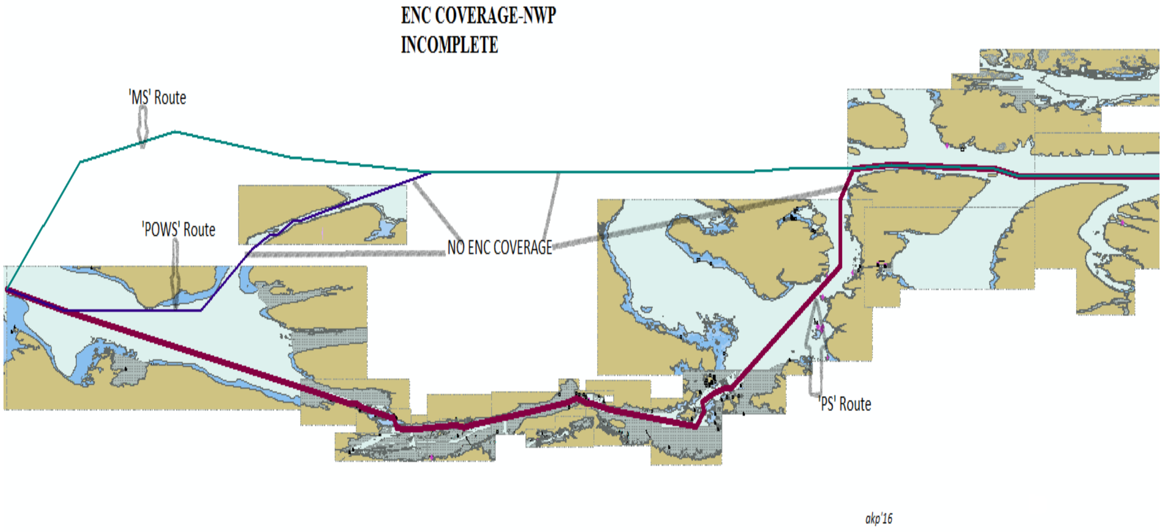
Source: "Ice Navigation in Canadian Waters" published by Icebreaking Program, Maritime Services, Canadian Coast Guard, Fisheries, and Oceans Canada, Ottawa, Ontario, revised August 2012.

Appendix 9: IMO; Proposed e-navigation Architecture (2015-2019)



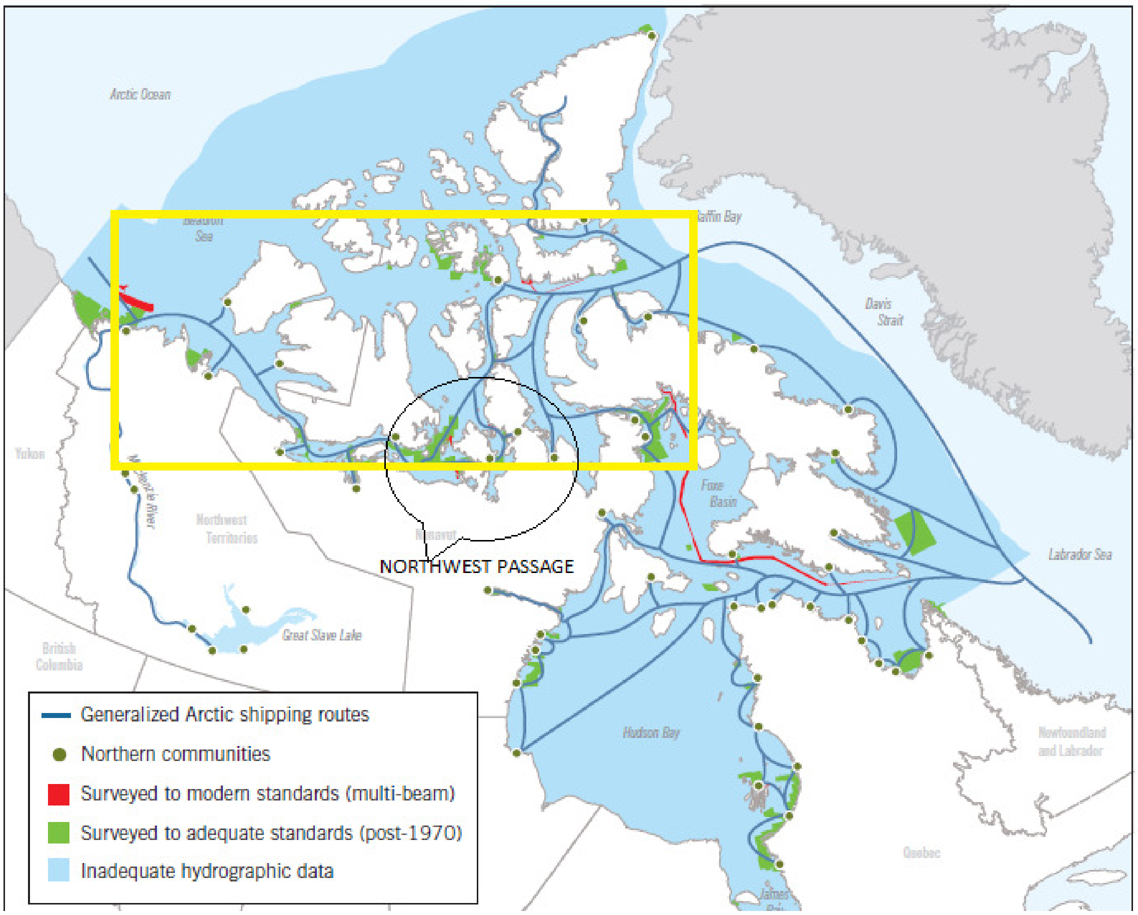
Source: IMO- *Draft e-navigation Strategy Implementation Plan, Annex 7, PP.19; NSCR 1/28*

Appendix 10: Non-ENC Coverage Areas: Northwest Passage



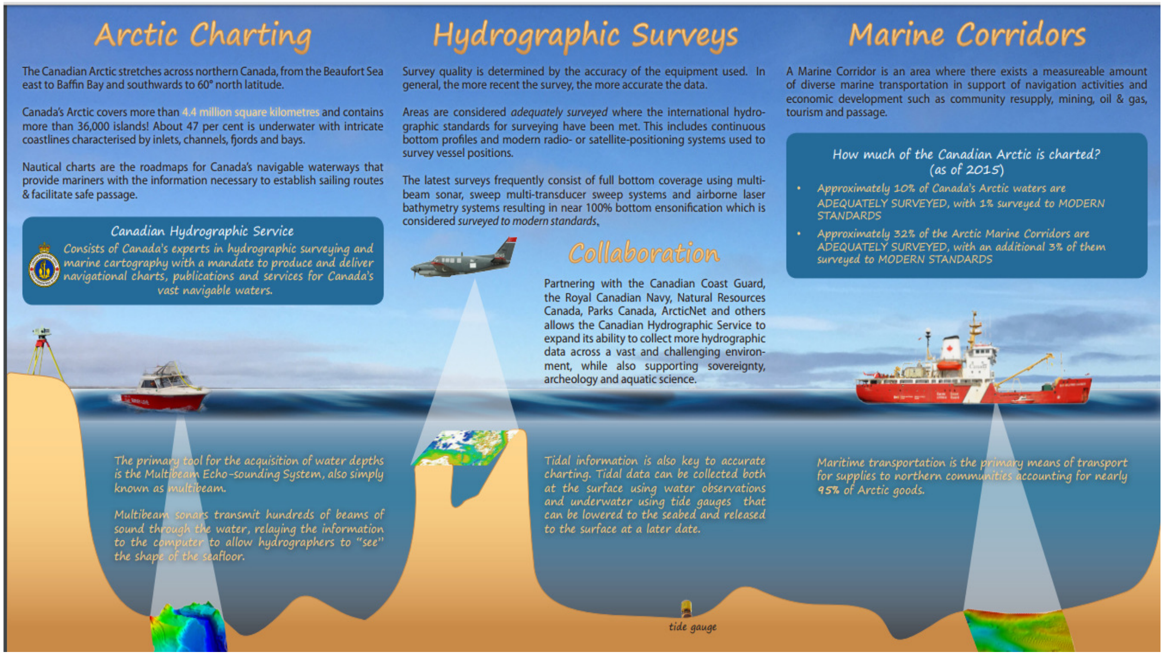
Source: Adapted from (Govt. of Canada-A, 2016), *2014 Fall Report of the Commissioner of the Environment and Sustainable Development,* Retrieved 03 23 2016, from http://www.oag-bvg.gc.ca/internet/English/parl_cesd_201410_03_e_39850.html.

Appendix 11: Extent of Hydrographic Survey: Canadian Arctic



Source: Adapted from (Govt. of Canada-A, 2016), *2014 Fall Report of the Commissioner of the Environment and Sustainable Development,* Retrieved 03 23 2016, from http://www.oag-bvg.gc.ca/internet/English/parl_cesd_201410_03_e_39850.html.

Appendix 12: Canadian Arctic- Charting and Surveys



Arctic Charting

The Canadian Arctic stretches across northern Canada, from the Beaufort Sea east to Baffin Bay and southwards to 60° north latitude.

Canada's Arctic covers more than 4.4 million square kilometres and contains more than 36,000 islands! About 47 per cent is underwater with intricate coastlines characterised by inlets, channels, fjords and bays.

Nautical charts are the roadmaps for Canada's navigable waterways that provide mariners with the information necessary to establish sailing routes & facilitate safe passage.

Canadian Hydrographic Service

Consists of Canada's experts in hydrographic surveying and marine cartography with a mandate to produce and deliver navigational charts, publications and services for Canada's vast navigable waters.

The primary tool for the acquisition of water depths is the Multibeam Echo-sounding System, also simply known as multibeam.

Multibeam sonars transmit hundreds of beams of sound through the water, relaying the information to the computer to allow hydrographers to "see" the shape of the seafloor.

Hydrographic Surveys

Survey quality is determined by the accuracy of the equipment used. In general, the more recent the survey, the more accurate the data.

Areas are considered *adequately surveyed* where the international hydrographic standards for surveying have been met. This includes continuous bottom profiles and modern radio- or satellite-positioning systems used to survey vessel positions.

The latest surveys frequently consist of full bottom coverage using multibeam sonar, sweep multi-transducer sweep systems and airborne laser bathymetry systems resulting in near 100% bottom ensonification which is considered *surveyed to modern standards*.

Collaboration

Partnering with the Canadian Coast Guard, the Royal Canadian Navy, Natural Resources Canada, Parks Canada, ArcticNet and others allows the Canadian Hydrographic Service to expand its ability to collect more hydrographic data across a vast and challenging environment, while also supporting sovereignty, archeology and aquatic science.

Tidal information is also key to accurate charting. Tidal data can be collected both at the surface using water observations and underwater using tide gauges that can be lowered to the seabed and released to the surface at a later date.

Marine Corridors

A Marine Corridor is an area where there exists a measureable amount of diverse marine transportation in support of navigation activities and economic development such as community resupply, mining, oil & gas, tourism and passage.

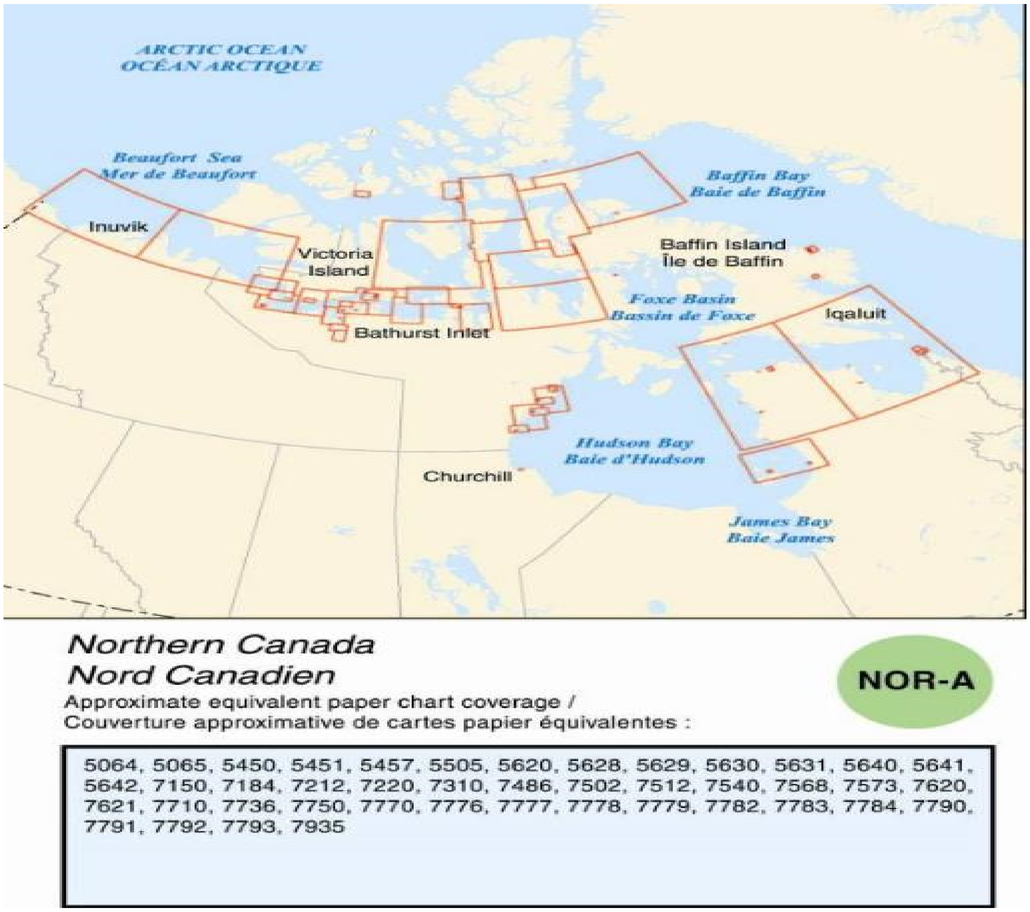
How much of the Canadian Arctic is charted?
(as of 2015)

- *Approximately 10% of Canada's Arctic waters are ADEQUATELY SURVEYED, with 1% surveyed to MODERN STANDARDS*
- *Approximately 32% of the Arctic Marine Corridors are ADEQUATELY SURVEYED, with an additional 3% of them surveyed to MODERN STANDARDS*

Maritime transportation is the primary means of transport for supplies to northern communities accounting for nearly ***95%*** *of Arctic goods.*

Source: From (Fisheries and Oceans Canada-D, 2016) retrieved August 01, 2016 from http://www.charts.gc.ca/arctic-arctique/index-eng.asp

Appendix 13: ENC coverage of the Canadian Arctic:



Northern Canada
Nord Canadien
Approximate equivalent paper chart coverage /
Couverture approximative de cartes papier équivalentes :

5064, 5065, 5450, 5451, 5457, 5505, 5620, 5628, 5629, 5630, 5631, 5640, 5641, 5642, 7150, 7184, 7212, 7220, 7310, 7486, 7502, 7512, 7540, 7568, 7573, 7620, 7621, 7710, 7736, 7750, 7770, 7776, 7777, 7778, 7779, 7782, 7783, 7784, 7790, 7791, 7792, 7793, 7935

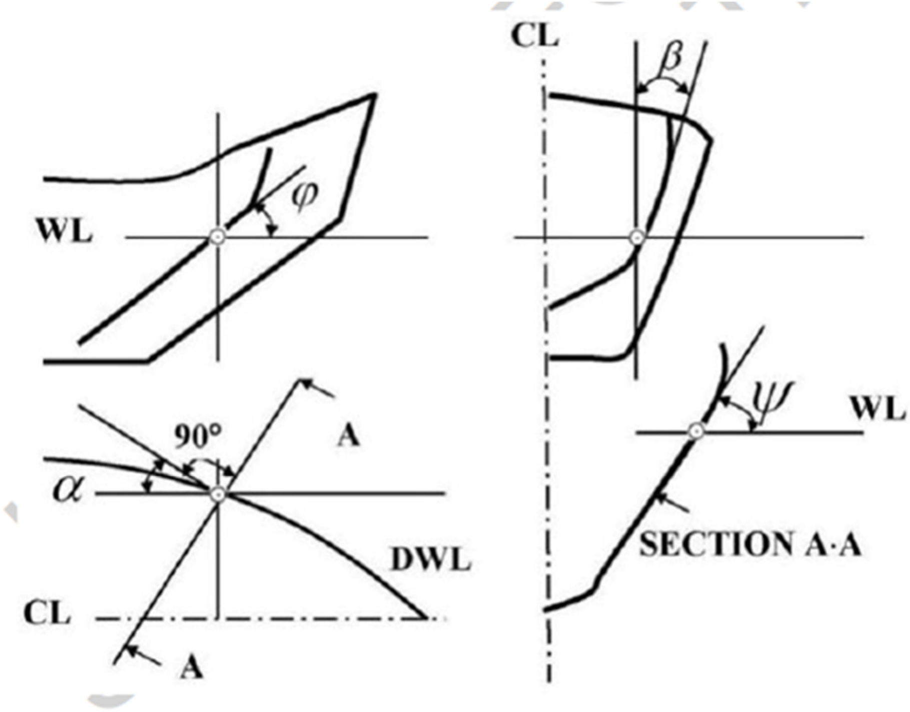
Source: From (Fisheries and Oceans Canada-B, 2016), retrieved March 23, 2016, from

http://www.charts.gc.ca/charts-cartes/digital-electronique/preview/vector/NOR-A-eng.asp

Appendix 14: IMO delineated boundary: Spatial extent of Arctic Waters

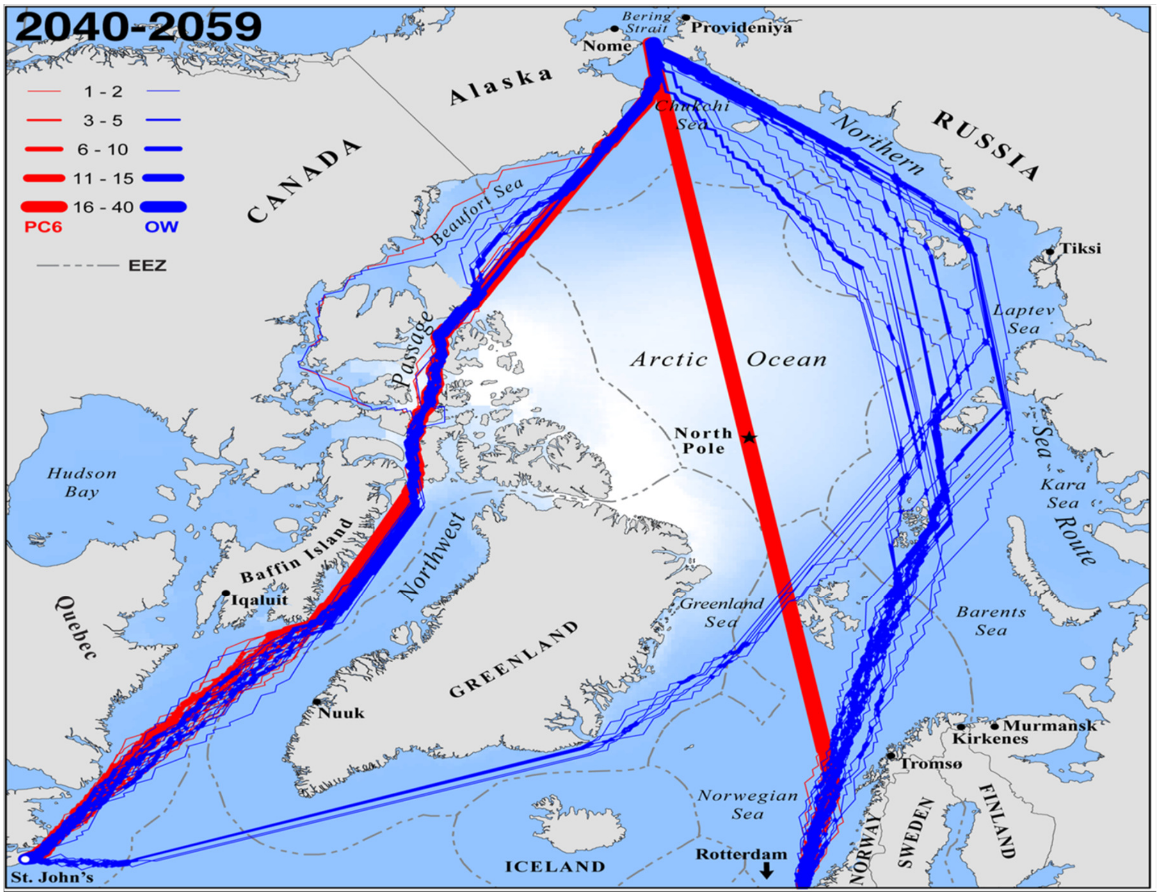
Source: From (IMO- Draft Polar Code, 2014), pp.3

Appendix 15: Definition of hull angles –Ice class vessels/Icebreakers



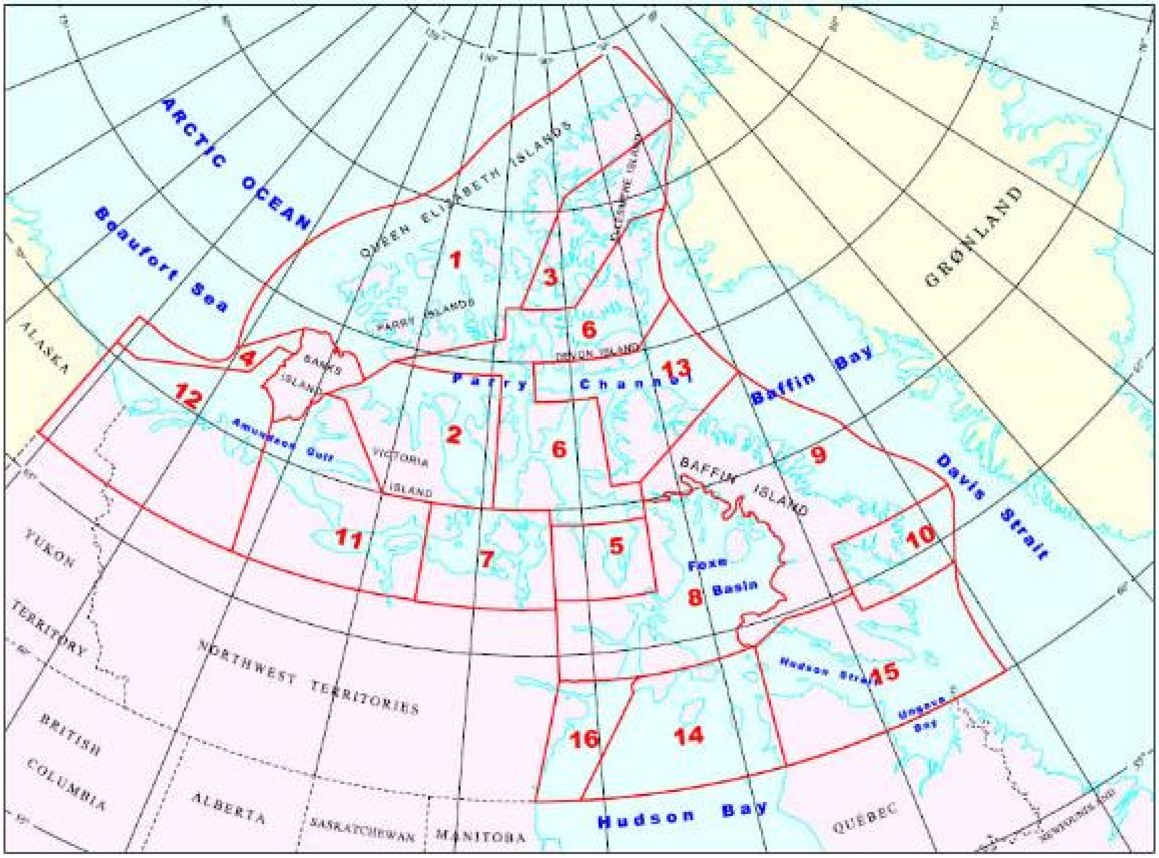
Source: From “Design of Icebreaking Ships” by Kaj Riska, 2010

Appendix 16: Projected Navigation Routes (September) in the Arctic (2040-2059)



Source: From (Smith & Stephenson, 2013). Retrieved January 4, 2016, from http://www.sscnet.ucla.edu/geog/downloads/297/554.pdf

Appendix 17: Shipping control safety zones-Canadian Arctic



Source: From (Transport Canada, 2012). Retrieved February 14, 2016, from

https://www.tc.gc.ca/eng/marinesafety/tp-tp12259-appendicies-2872.htm

Appendix 18: Zone/Date Matrix- Canadian Arctic

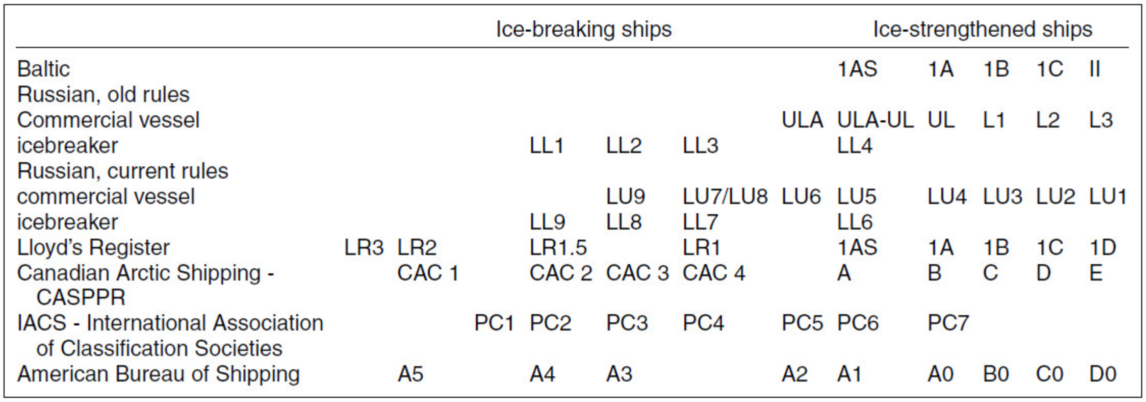
Column I	Column II	Column III	Column IV	Column V	Column VI	Column VII	Column VIII	Column IX	Column X	Column XI	Column XII	Column XIII	Column XIV	Column XV	Column XVI	Column XVII	
Item	Category	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11	Zone 12	Zone 13	Zone 14	Zone 15	Zone 16
1	Arctic Class 10	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
2	Arctic Class 8	Jul. 1 to Oct. 15	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
3	Arctic Class 7	Aug. 1 to Sept. 30	Aug. 1 to Nov. 30	Jul. 1 to Dec. 31	Jul. 1 to Dec. 15	Jul. 1 to Dec. 15	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
4	Arctic Class 6	Aug. 15 to Sept. 15	Aug. 1 to Oct. 31	Jul. 15 to Nov. 30	Jul. 15 to Nov. 30	Aug. 1 to Oct. 15	Jul. 15 to Feb. 28	Jul. 1 to Mar. 31	Jul. 1 to Mar. 31	All Year	All Year	Jul. 1 to	All Year	All Year	All Year	All Year	All Year
5	Arctic Class 4	Aug. 15 to Sept. 15	Aug. 15 to Oct. 15	Jul. 15 to Oct. 31	Jul. 15 to Nov. 15	Aug. 15 to Sept. 30	Jul. 20 to Dec. 31	Jul. 15 to Jan. 15	Jul. 15 to Jan. 15	Jul. 10 to Mar. 31	Jul. 10 to Feb. 28	Jul. 5 to Jan. 15	June 1 to Jan. 31	June 1 to Feb. 15	June 15 to Feb. 15	June 15 to Mar. 15	June 1 to Feb. 15
6	Arctic	Aug.	Aug.	Jul.	Jul.	Aug.	Aug. 1	Jul.	Jul.	Jul.	Jul.	Jul. 5	June	June	June	June	Jun

Column I	Column II	Column III	Column IV	Column V	Column VI	Column VII	Column VIII	Column IX	Column X	Column XI	Column XII	Column XIII	Column XIV	Column XV	Column XVI	Column XVII	
Item	Category	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11	Zone 12	Zone 13	Zone 14	Zone 15	Zone 16
	Class 3	20 toSept. 15	20 to Sept. 30	25 to Oct. 15	20 to Nov. 5	20 to Sept. 25	to Nov. 30	20 to Dec. 15	20 to Dec. 31	20 to Jan. 20	15 to Jan. 25	to Dec. 15	10 to Dec. 31	10 to Dec. 31	20 to Jan. 10	20 to Jan. 31	e 5 to Jan. 10
7	Arctic Class 2	No Entry	No Entry	Aug. 15 to Sept. 30	Aug. 1 to Oct. 31	No Entry	Aug. 15 to Nov. 20	Aug. 1 to Nov. 20	Aug. 1 to Nov. 30	Aug. 1 to Dec. 20	Jul. 25 to Dec. 20	Jul. 10 to Nov. 20	June 15 to Dec. 5	June 25 to Nov. 22	June 25 to Dec. 10	June 25 to Dec. 20	June 10 to Dec. 10
8	Arctic Class 1A	No Entry	No Entry	Aug. 20 to Sept. 15	Aug. 20 to Sept. 30	No Entry	Aug. 25 to Oct. 31	Aug. 10 to Nov. 5	Aug. 10 to Nov. 20	Aug. 10 to Dec. 10	Aug. 1 to Dec. 10	Jul. 15 to Nov. 10	Jul. 1 to Nov. 10	Jul. 15 to Oct. 31	Jul. 1 to Nov. 30	Jul. 1 to Dec. 10	June 20 to Nov. 30
9	Arctic Class 1	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 25 to Sept. 30	Aug. 10 to Oct. 15	Aug. 10 to Oct. 31	Aug. 10 to Oct. 31	Aug. 1 to Oct. 31	Jul. 15 to Oct. 20	Jul. 1 to Oct. 31	Jul. 15 to Oct. 15	Jul. 1 to Nov. 30	Jul. 1 to Nov. 30	June 20 to Nov. 15
10	Type A	No Entry	No Entry	Aug. 20 to Sept. 10	Aug. 20 to Sept. 20	No Entry	Aug. 15 to Oct. 15	Aug. 1 to Oct. 25	Aug. 1 to Nov. 10	Aug. 1 to Nov. 20	Jul. 25 to Nov. 20	Jul. 10 to Oct. 31	June 15 to Nov. 10	June 25 to Oct. 22	June 25 to Nov. 30	June 25 to Dec. 5	June 20 to Nov

Column I	Column II	Column III	Column IV	Column V	Column VI	Column VII	Column VIII	Column IX	Column X	Column XI	Column XII	Column XIII	Column XIV	Column XV	Column XVI	Column XVII	
Item	Category	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11	Zone 12	Zone 13	Zone 14	Zone 15	Zone 16
																	. 20
11	Type B	No Entry	No Entry	Aug. 20 to Sept. 5	Aug. 20 to Sept. 15	No Entry	Aug. 25 to Sept. 30	Aug. 10 to Oct. 15	Aug. 10 to Oct. 31	Aug. 10 to Oct. 31	Aug. 1 to Oct. 31	Jul. 15 to Oct. 20	Jul. 1 to Oct. 25	Jul. 15 to Oct. 15	Jul. 1 to Nov. 30	Jul. 1 to Nov. 30	June 20 to Nov. 10
12	Type C	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 25 to Sept. 25	Aug. 10 to Oct. 10	Aug. 10 to Oct. 25	Aug. 10 to Oct. 25	Aug. 1 to Oct. 25	Jul. 15 to Oct. 15	Jul. 1 to Oct. 25	Jul. 15 to Oct. 10	Jul. 1 to Nov. 25	Jul. 1 to Nov. 25	June 25 to Nov. 10
13	Type D	No Entry	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 10 to Oct. 5	Aug. 15 to Oct. 20	Aug. 15 to Oct. 20	Aug. 5 to Oct. 20	Jul. 15 to Oct. 10	Jul. 1 to Oct. 20	Jul. 30 to Sept. 30	Jul. 10 to Nov. 10	Jul. 5 to Nov. 10	Jul. 1 to Oct. 31
14	Type E	No Entry	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 10 to Sept. 30	Aug. 20 to Oct. 20	Aug. 20 to Oct. 15	Aug. 10 to Oct. 20	Jul. 15 to Sept. 30	Jul. 1 to Oct. 20	Aug. 15 to Sept. 20	Jul. 20 to Oct. 31	Jul. 20 to Nov. 5	Jul. 1 to Oct. 31

Source: Arctic Shipping Pollution Prevention Regulations, Schedule VII, retrieved August 12, 2016 from http://laws-lois.justice.gc.ca/eng/regulations/C.R.C., c. 353/page-11.html#h-18

Appendix 19: Approximate Equivalence Table: Ice Classification of Ships



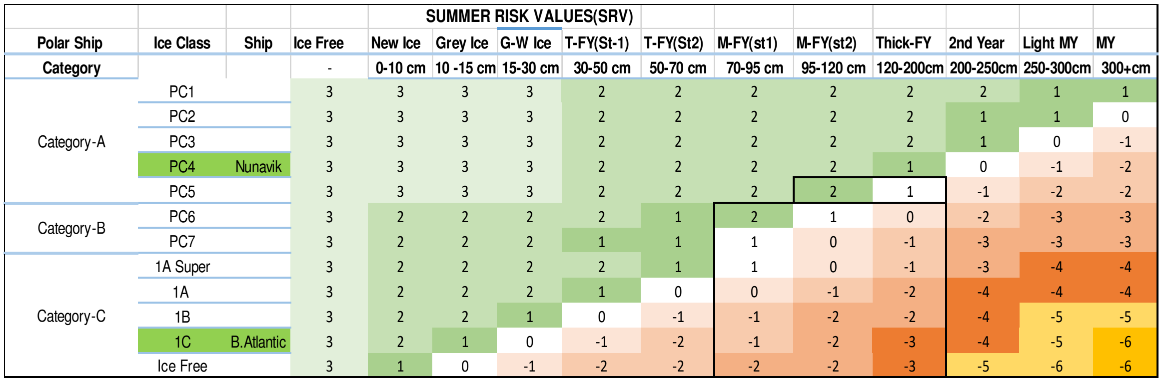
	Ice-breaking ships							Ice-strengthened ships				
Baltic								1AS	1A	1B	1C	II
Russian, old rules												
Commercial vessel							ULA	ULA-UL	UL	L1	L2	L3
icebreaker				LL1	LL2	LL3		LL4				
Russian, current rules												
commercial vessel					LU9	LU7/LU8	LU6	LU5	LU4	LU3	LU2	LU1
icebreaker				LL9	LL8	LL7		LL6				
Lloyd's Register	LR3	LR2		LR1.5		LR1		1AS	1A	1B	1C	1D
Canadian Arctic Shipping - CASPPR		CAC 1		CAC 2	CAC 3	CAC 4		A	B	C	D	E
IACS - International Association of Classification Societies			PC1	PC2	PC3	PC4	PC5	PC6	PC7			
American Bureau of Shipping		A5		A4	A3		A2	A1	A0	B0	C0	D0

Sources: Appolonov and others 2006; Lamb 2004, International Association of Classification Societies 2006, Bridges (2004), Lloyd's Register (London) 7 September 2004; Eyres 2001; National Research Council 2007.

Source: From "*Simulations of shipping along Arctic routes: comparison,*

Analysis and economic perspectives "by Lasserre F., 2014, Polar Record 51 (258): 239–259 (2015).

Appendix 10: Table of Summer Risk Values: POLARIS



							SUMMER RISK VALUES(SRV)							
Polar Ship	Ice Class	Ship	Ice Free	New Ice	Grey Ice	G-W Ice	T-FY(St-1)	T-FY(St2)	M-FY(st1)	M-FY(st2)	Thick-FY	2nd Year	Light MY	MY
Category			-	0-10 cm	10 -15 cm	15-30 cm	30-50 cm	50-70 cm	70-95 cm	95-120 cm	120-200cm	200-250cm	250-300cm	300+cm
Category-A	PC1		3	3	3	3	2	2	2	2	2	2	1	1
	PC2		3	3	3	3	2	2	2	2	2	1	1	0
	PC3		3	3	3	3	2	2	2	2	2	1	0	-1
	PC4	Nunavik	3	3	3	3	2	2	2	2	1	0	-1	-2
	PC5		3	3	3	3	2	2	2	2	1	-1	-2	-2
Category-B	PC6		3	2	2	2	2	1	2	1	0	-2	-3	-3
	PC7		3	2	2	2	1	1	1	0	-1	-3	-3	-3
Category-C	1A Super		3	2	2	2	2	1	1	0	-1	-3	-4	-4
	1A		3	2	2	2	1	0	0	-1	-2	-4	-4	-4
	1B		3	2	2	1	0	-1	-1	-2	-2	-4	-5	-5
	1C	B.Atlantic	3	2	1	0	-1	-2	-1	-2	-3	-4	-5	-6
	Ice Free		3	1	0	-1	-2	-2	-2	-2	-3	-5	-6	-6

Escorted Operations		Add +10	
Decayed Ice	PC-5	Add+1	MFY(2)-TFY
(Add +1 to WRV)	PC6-Ice Fr	Add+1	MFY(1)-TFY

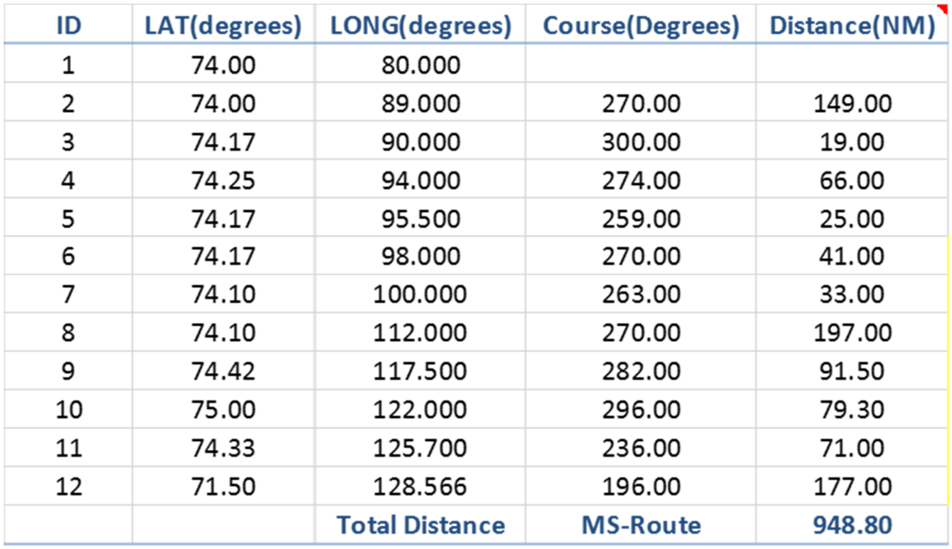
Source: Adapted from IMO-Maritime Safety Committee, 94th session, "Technical Background to POLARIS" Retrieved May 10, 2016 from http://www.iacs.org.uk/document/public/Publications/Submissions_to_imo/pdf/consideration_and_adoption_of_amendments_to_mandatory_instruments_pdf2417.pdf

Appendix 21: Table of Routes and Distances- Northwest Passage

Prince of Wales Straits Route:

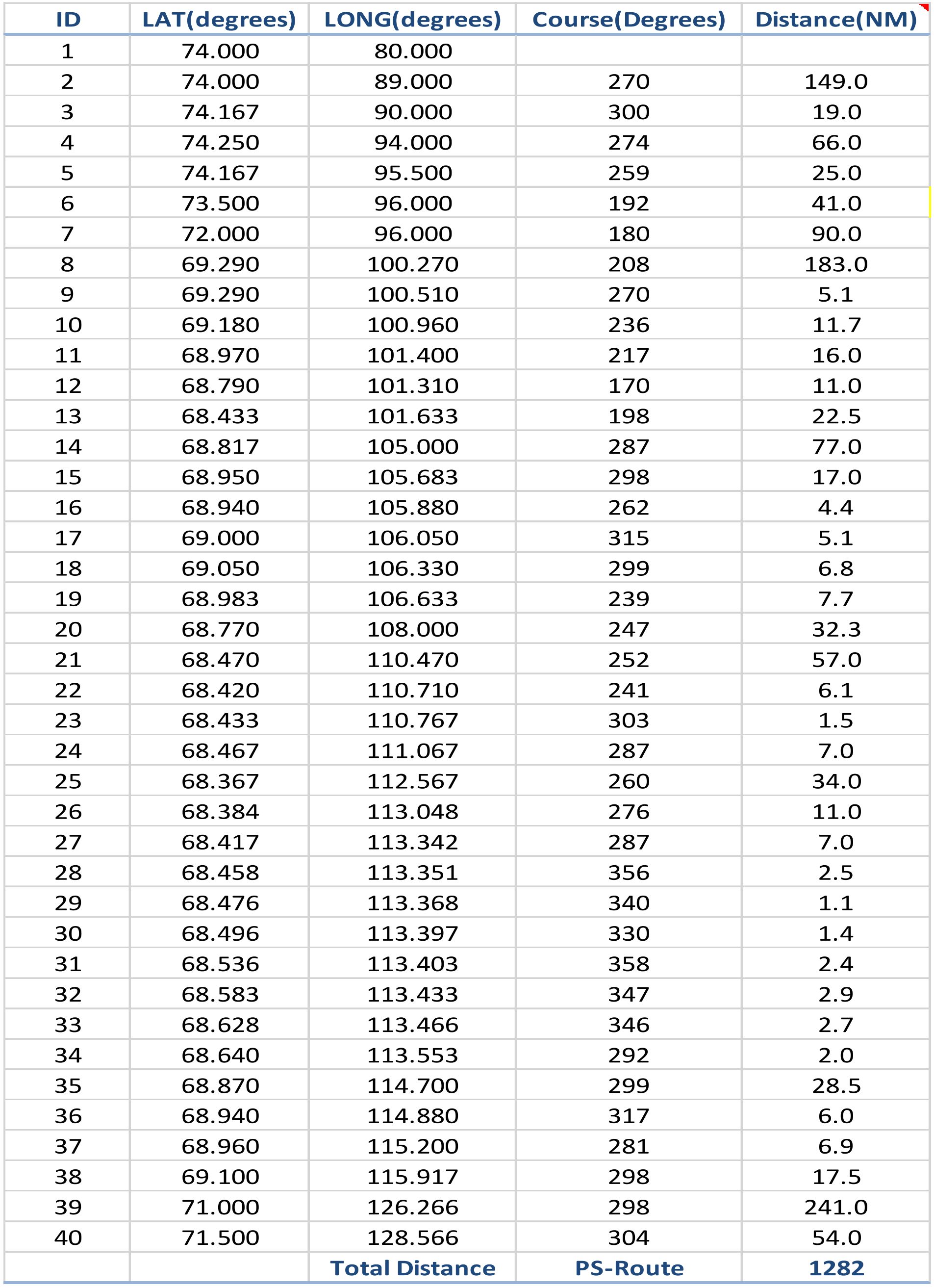
ID	LAT(degrees)	LONG(degrees)	Course(Degrees)	Distance(NM)
1	74.00	80.000		
2	74.00	89.000	270	149
3	74.17	90.000	300	19
4	74.25	94.000	274	66
5	74.17	95.500	259	25
6	74.17	98.000	270	41
7	74.10	100.000	263	33
8	74.10	112.000	270	197
9	73.25	116.000	233	85
10	73.00	117.167	234	25
11	73.00	117.410	270	4.4
12	72.73	117.960	211	19
13	72.70	118.300	254	6.4
14	72.38	119.000	213	23
15	71.00	121.000	204	91
16	71.00	126.264	270	103
17	71.50	128.566	304	54
		Total Distance	**POWS-Route**	**941**

M’Clure Strait Route:



ID	LAT(degrees)	LONG(degrees)	Course(Degrees)	Distance(NM)
1	74.00	80.000		
2	74.00	89.000	270.00	149.00
3	74.17	90.000	300.00	19.00
4	74.25	94.000	274.00	66.00
5	74.17	95.500	259.00	25.00
6	74.17	98.000	270.00	41.00
7	74.10	100.000	263.00	33.00
8	74.10	112.000	270.00	197.00
9	74.42	117.500	282.00	91.50
10	75.00	122.000	296.00	79.30
11	74.33	125.700	236.00	71.00
12	71.50	128.566	196.00	177.00
		Total Distance	**MS-Route**	**948.80**

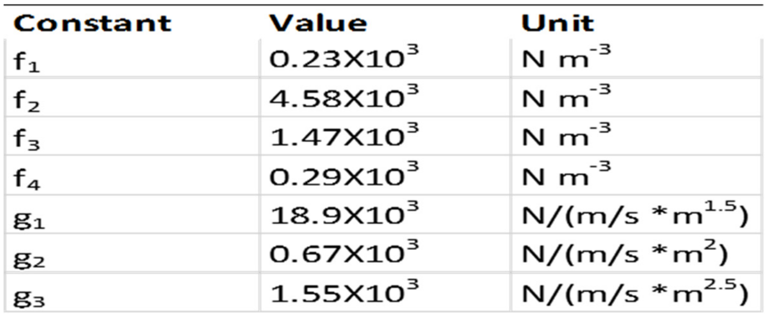
Peel Sound Route:



ID	LAT(degrees)	LONG(degrees)	Course(Degrees)	Distance(NM)
1	74.000	80.000		
2	74.000	89.000	270	149.0
3	74.167	90.000	300	19.0
4	74.250	94.000	274	66.0
5	74.167	95.500	259	25.0
6	73.500	96.000	192	41.0
7	72.000	96.000	180	90.0
8	69.290	100.270	208	183.0
9	69.290	100.510	270	5.1
10	69.180	100.960	236	11.7
11	68.970	101.400	217	16.0
12	68.790	101.310	170	11.0
13	68.433	101.633	198	22.5
14	68.817	105.000	287	77.0
15	68.950	105.683	298	17.0
16	68.940	105.880	262	4.4
17	69.000	106.050	315	5.1
18	69.050	106.330	299	6.8
19	68.983	106.633	239	7.7
20	68.770	108.000	247	32.3
21	68.470	110.470	252	57.0
22	68.420	110.710	241	6.1
23	68.433	110.767	303	1.5
24	68.467	111.067	287	7.0
25	68.367	112.567	260	34.0
26	68.384	113.048	276	11.0
27	68.417	113.342	287	7.0
28	68.458	113.351	356	2.5
29	68.476	113.368	340	1.1
30	68.496	113.397	330	1.4
31	68.536	113.403	358	2.4
32	68.583	113.433	347	2.9
33	68.628	113.466	346	2.7
34	68.640	113.553	292	2.0
35	68.870	114.700	299	28.5
36	68.940	114.880	317	6.0
37	68.960	115.200	281	6.9
38	69.100	115.917	298	17.5
39	71.000	126.266	298	241.0
40	71.500	128.566	304	54.0
		Total Distance	**PS-Route**	**1282**

Source: From nautical paper charts of the Northwest Passage, calculations by Author, March 2016

Appendix 22: Constants and Symbols- Ship-Transit Model

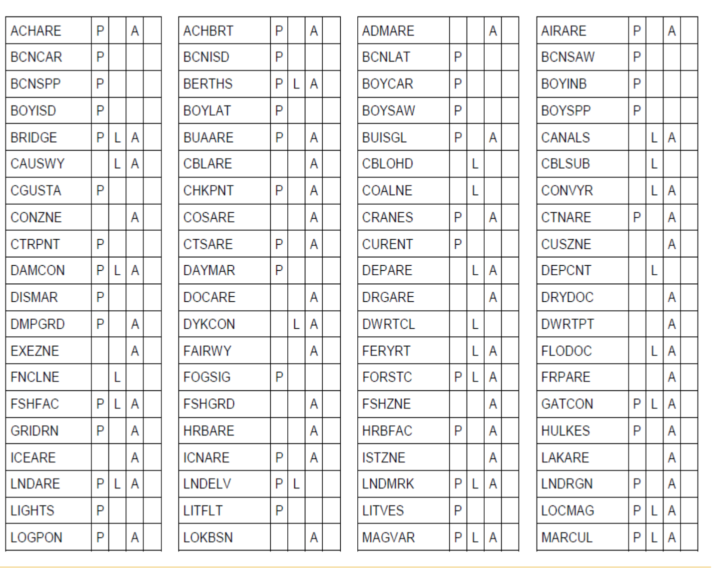


Constant	Value	Unit
f_1	$0.23X10^3$	$N\ m^{-3}$
f_2	$4.58X10^3$	$N\ m^{-3}$
f_3	$1.47X10^3$	$N\ m^{-3}$
f_4	$0.29X10^3$	$N\ m^{-3}$
g_1	$18.9X10^3$	$N/(m/s * m^{1.5})$
g_2	$0.67X10^3$	$N/(m/s * m^{2})$
g_3	$1.55X10^3$	$N/(m/s * m^{2.5})$

Symbol	Value	Meaning
h_i		level ice thickness
ϕ		bow angle
g		acceleration due to gravity
L		Ship Length
L_{bow}		length of ship bow
L_{par}		length of parallel body
B		ship maximum breadth
T		ship draught
V_{ow}		open water speed
$\tilde{u}$		estimated ship speed
P_5		Propulsion Power
D_p		Propeller Diameter
V		Average ship speed
K_e		Quality Coefficient-Bollard Pull
K_e	Single Screw	0.78
K_e	Twin screw	0.98

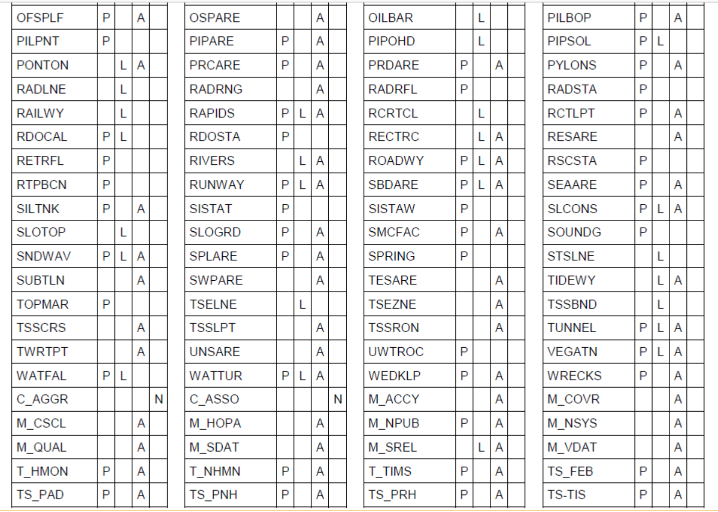
Source: From “A system for route optimization in ice-covered waters,” by Ville Kotovirta, Risto Jalonen Lars Axell, Kaj Riska, Robin Berglund, 2008, *Cold Regions Science and Technology* 55 (2009) 52–62 © Elsevier B.V.

Appendix 23: IHO-List of Geo-objects and Meta-objects-ENC-S57 Charts



ACHARE	P		A		ACHBRT	P		A		ADMARE			A		AIRARE	P		A	
BCNCAR	P				BCNISD	P				BCNLAT	P				BCNSAW	P			
BCNSPP	P				BERTHS	P	L	A		BOYCAR	P				BOYINB	P			
BOYISD	P				BOYLAT	P				BOYSAW	P				BOYSPP	P			
BRIDGE	P	L	A		BUAARE	P		A		BUISGL	P		A		CANALS		L	A	
CAUSWY		L	A		CBLARE			A		CBLOHD		L			CBLSUB		L		
CGUSTA	P				CHKPNT	P		A		COALNE		L			CONVYR		L	A	
CONZNE			A		COSARE			A		CRANES	P		A		CTNARE	P		A	
CTRPNT	P				CTSARE	P		A		CURENT	P				CUSZNE			A	
DAMCON	P	L	A		DAYMAR	P				DEPARE		L	A		DEPCNT		L		
DISMAR	P				DOCARE			A		DRGARE			A		DRYDOC			A	
DMPGRD	P		A		DYKCON		L	A		DWRTCL		L			DWRTPT			A	
EXEZNE			A		FAIRWY			A		FERYRT		L	A		FLODOC		L	A	
FNCLNE		L			FOGSIG	P				FORSTC	P	L	A		FRPARE			A	
FSHFAC	P	L	A		FSHGRD			A		FSHZNE			A		GATCON	P	L	A	
GRIDRN	P		A		HRBARE			A		HRBFAC	P		A		HULKES	P		A	
ICEARE			A		ICNARE	P		A		ISTZNE			A		LAKARE			A	
LNDARE	P	L	A		LNDELV	P	L			LNDMRK	P	L	A		LNDRGN	P		A	
LIGHTS	P				LITFLT	P				LITVES	P				LOCMAG	P	L	A	
LOGPON	P		A		LOKBSN			A		MAGVAR	P	L	A		MARCUL	P	L	A	

OBJECT



OFSPLF	P		A		OSPARE			A		OILBAR		L			PILBOP	P		A	
PILPNT	P				PIPARE	P		A		PIPOHD		L			PIPSOL	P	L		
PONTON		L	A		PRCARE	P		A		PRDARE	P		A		PYLONS	P		A	
RADLNE		L			RADRNG			A		RADRFL	P				RADSTA	P			
RAILWY		L			RAPIDS	P	L	A		RCRTCL		L			RCTLPT	P		A	
RDOCAL	P	L			RDOSTA	P				RECTRC		L	A		RESARE			A	
RETRFL	P				RIVERS		L	A		ROADWY	P	L	A		RSCSTA	P			
RTPBCN	P				RUNWAY	P	L	A		SBDARE	P	L	A		SEAARE	P		A	
SILTNK	P		A		SISTAT	P				SISTAW	P				SLCONS	P	L	A	
SLOTOP		L			SLOGRD	P		A		SMCFAC	P		A		SOUNDG	P			
SNDWAV	P	L	A		SPLARE	P		A		SPRING	P				STSLNE		L		
SUBTLN			A		SWPARE			A		TESARE			A		TIDEWY		L	A	
TOPMAR	P				TSELNE		L			TSEZNE			A		TSSBND		L		
TSSCRS			A		TSSLPT			A		TSSRON			A		TUNNEL	P	L	A	
TWRTPT			A		UNSARE			A		UWTROC	P				VEGATN	P	L	A	
WATFAL	P	L			WATTUR	P	L	A		WEDKLP	P		A		WRECKS	P		A	
C_AGGR				N	C_ASSO				N	M_ACCY			A		M_COVR			A	
M_CSCL			A		M_HOPA			A		M_NPUB	P		A		M_NSYS			A	
M_QUAL			A		M_SDAT			A		M_SREL		L	A		M_VDAT			A	
T_HMON	P		A		T_NHMN	P		A		T_TIMS	P		A		TS_FEB	P		A	
TS_PAD	P		A		TS_PNH	P		A		TS_PRH	P		A		TS-TIS	P		A	

GEOMETRIC PRIMITIVES

P: POINT

A: AREA

L: LINE

METAOBJECTS

M_COVR

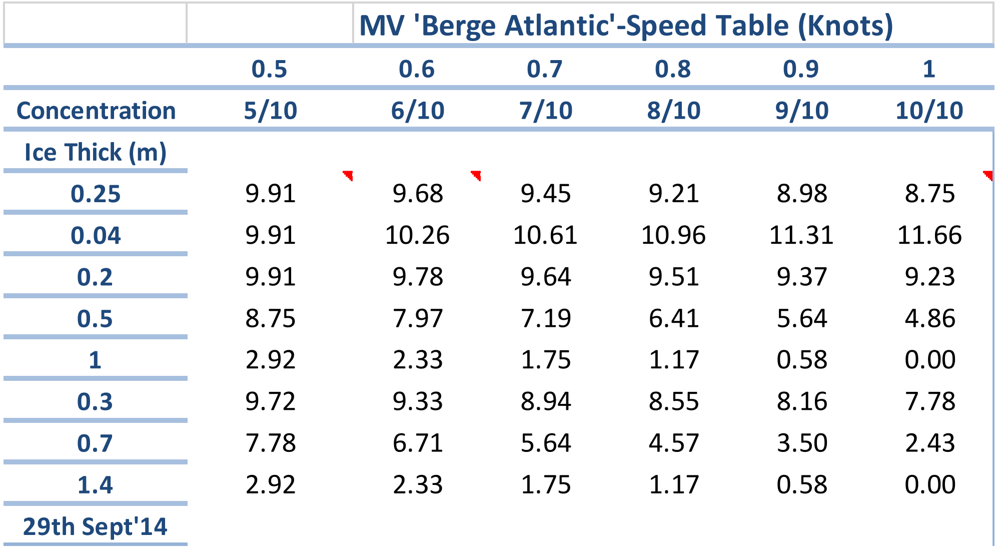
M_OUAL

Source: Adapted from: IHO object catalogue: S-57 Appendix E

November 2000.

CODE	MEANING
LNDARE	LANDAREA
M_COVR	METAOBJECT: Must cover any part of the cell that does not have geographical data
SOUNDG	DEPTH SOUNDING
OBSTN	OBSTRUCTION
UNSARE	UNSURVEYED AREA

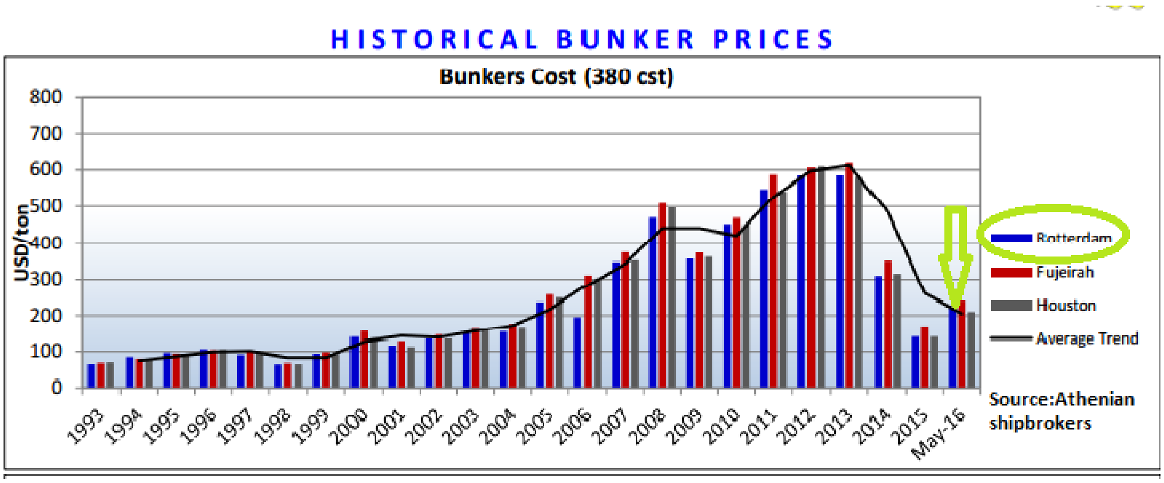
Appendix 24: Speed Performance Table- ‘Berge Atlantic’



		MV 'Berge Atlantic'-Speed Table (Knots)				
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1**
Concentration	**5/10**	**6/10**	**7/10**	**8/10**	**9/10**	**10/10**
Ice Thick (m)						
0.25	9.91	9.68	9.45	9.21	8.98	8.75
0.04	9.91	10.26	10.61	10.96	11.31	11.66
0.2	9.91	9.78	9.64	9.51	9.37	9.23
0.5	8.75	7.97	7.19	6.41	5.64	4.86
1	2.92	2.33	1.75	1.17	0.58	0.00
0.3	9.72	9.33	8.94	8.55	8.16	7.78
0.7	7.78	6.71	5.64	4.57	3.50	2.43
1.4	2.92	2.33	1.75	1.17	0.58	0.00
29th Sept'14						

Source: Author

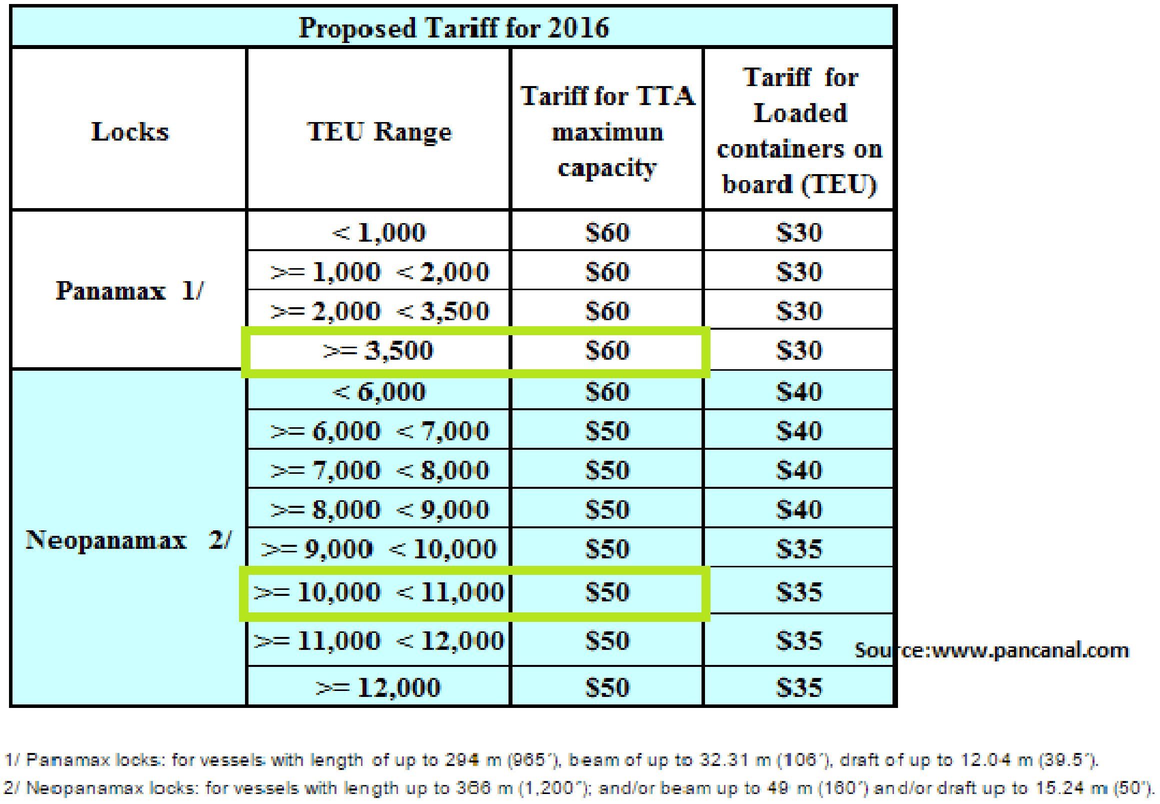
Appendix 25: Bunker Fuel –Historical Prices



Source: (Athenian Shipbrokers, 2016), retrieved July 10, 2016, from

http://www.hellenicshippingnews.com/athenian-shipbrokers-s-a-monthly-report-june-2016/

Appendix 26: Panama Canal Tariff (2016)



Proposed Tariff for 2016			
Locks	TEU Range	Tariff for TTA maximun capacity	Tariff for Loaded containers on board (TEU)
Panamax 1/	< 1,000	$60	$30
	>= 1,000 < 2,000	$60	$30
	>= 2,000 < 3,500	$60	$30
	>= 3,500	$60	$30
Neopanamax 2/	< 6,000	$60	$40
	>= 6,000 < 7,000	$50	$40
	>= 7,000 < 8,000	$50	$40
	>= 8,000 < 9,000	$50	$40
	>= 9,000 < 10,000	$50	$35
	>= 10,000 < 11,000	$50	$35
	>= 11,000 < 12,000	$50	$35
	>= 12,000	$50	$35

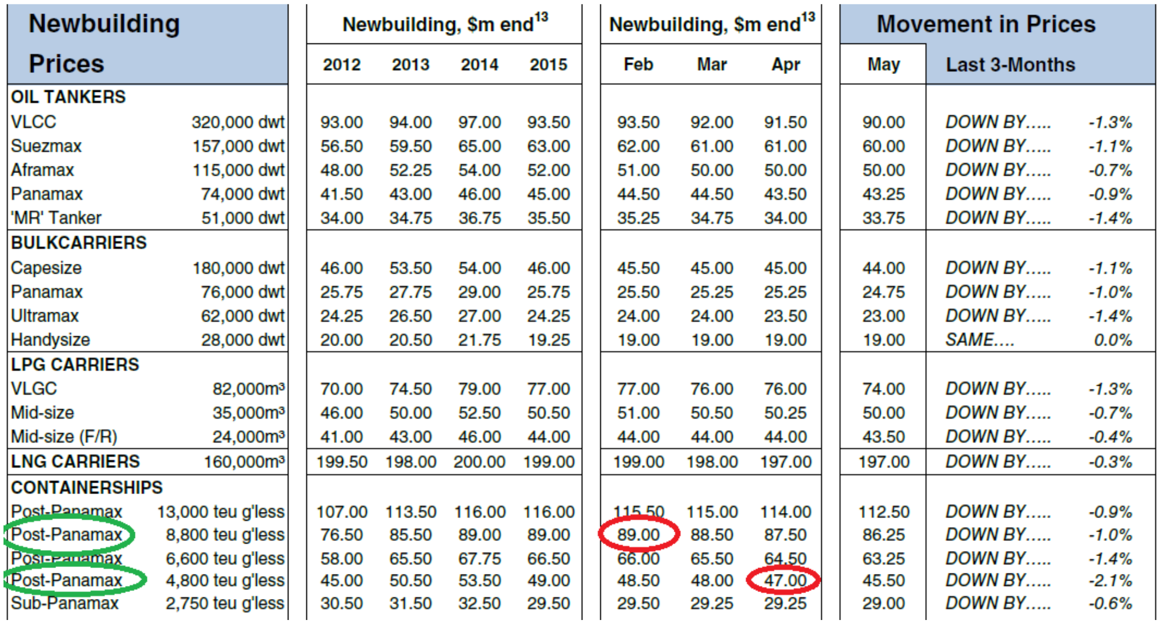
Source:www.pancanal.com

1/ Panamax locks: for vessels with length of up to 294 m (965´), beam of up to 32.31 m (106´), draft of up to 12.04 m (39.5´).
2/ Neopanamax locks: for vessels with length up to 366 m (1,200´); and/or beam up to 49 m (160´) and/or draft up to 15.24 m (50´).

Source: (Panama Canal Authority, 2016), retrieved July 05, 2016, from

https://www.pancanal.com/eng/op/tolls.html,

Appendix 27: Newbuilding Prices-2016



Newbuilding Prices		Newbuilding, $m end^{13}				Newbuilding, $m end^{13}			Movement in Prices		
		2012	2013	2014	2015	Feb	Mar	Apr	May	Last 3-Months	
OIL TANKERS											
VLCC	320,000 dwt	93.00	94.00	97.00	93.50	93.50	92.00	91.50	90.00	*DOWN BY.....*	*-1.3%*
Suezmax	157,000 dwt	56.50	59.50	65.00	63.00	62.00	61.00	61.00	60.00	*DOWN BY.....*	*-1.1%*
Aframax	115,000 dwt	48.00	52.25	54.00	52.00	51.00	50.00	50.00	50.00	*DOWN BY.....*	*-0.7%*
Panamax	74,000 dwt	41.50	43.00	46.00	45.00	44.50	44.50	43.50	43.25	*DOWN BY.....*	*-0.9%*
'MR' Tanker	51,000 dwt	34.00	34.75	36.75	35.50	35.25	34.75	34.00	33.75	*DOWN BY.....*	*-1.4%*
BULKCARRIERS											
Capesize	180,000 dwt	46.00	53.50	54.00	46.00	45.50	45.00	45.00	44.00	*DOWN BY.....*	*-1.1%*
Panamax	76,000 dwt	25.75	27.75	29.00	25.75	25.50	25.25	25.25	24.75	*DOWN BY.....*	*-1.0%*
Ultramax	62,000 dwt	24.25	26.50	27.00	24.25	24.00	24.00	23.50	23.00	*DOWN BY.....*	*-1.4%*
Handysize	28,000 dwt	20.00	20.50	21.75	19.25	19.00	19.00	19.00	19.00	*SAME....*	*0.0%*
LPG CARRIERS											
VLGC	82,000m³	70.00	74.50	79.00	77.00	77.00	76.00	76.00	74.00	*DOWN BY.....*	*-1.3%*
Mid-size	35,000m³	46.00	50.00	52.50	50.50	51.00	50.50	50.25	50.00	*DOWN BY.....*	*-0.7%*
Mid-size (F/R)	24,000m³	41.00	43.00	46.00	44.00	44.00	44.00	44.00	43.50	*DOWN BY.....*	*-0.4%*
LNG CARRIERS	160,000m³	199.50	198.00	200.00	199.00	199.00	198.00	197.00	197.00	*DOWN BY.....*	*-0.3%*
CONTAINERSHIPS											
Post-Panamax	13,000 teu g'less	107.00	113.50	116.00	116.00	115.50	115.00	114.00	112.50	*DOWN BY.....*	*-0.9%*
Post-Panamax	8,800 teu g'less	76.50	85.50	89.00	89.00	89.00	88.50	87.50	86.25	*DOWN BY.....*	*-1.0%*
Post-Panamax	6,600 teu g'less	58.00	65.50	67.75	66.50	66.00	65.50	64.50	63.25	*DOWN BY.....*	*-1.4%*
Post-Panamax	4,800 teu g'less	45.00	50.50	53.50	49.00	48.50	48.00	47.00	45.50	*DOWN BY.....*	*-2.1%*
Sub-Panamax	2,750 teu g'less	30.50	31.50	32.50	29.50	29.50	29.25	29.25	29.00	*DOWN BY.....*	*-0.6%*

Source: Adapted from, Clarkson Research, World Fleet Monitor Vol. 7, No. 6, June 2016, ISSN: 2042-0633, retrieved 30/6/2016 00:11:46 9165, from www.clarkson.net/wfr