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A Decision Support Model for Merchant Vessels Operating on the Arctic Sea

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Preface

This Master Thesis completes the work of my *Master of Science* degree in Marine Technology at the Norwegian University of Science and Technology (NTNU), and is the result of the work carried out during the spring semester of 2012.

The objective of this work has been to assess design aspects for vessels using the Northern Sea Route (NSR) in addition to the Suez Canal Route (SCR). Followed by development of a decision support model (DSM) to assess the potential financial benefit of using the NSR taking into account the costs of ship requirements to be fulfilled, encountered ice and the vessels performance thereafter with resulting fuel consumption and cost, in addition to operational and voyage expenses.

I would like to thank my responsible advisor at NTNU, Professor Sören Ehlers for valuable input, discussions, help and guidance throughout the work of this thesis. I would also like to thank Rüdiger von Bock und Polach for help and guidance with the ship merit factor.

Bergen, June, 2012

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Svenn Sætren Sørstrand

Summary

With the ice cap diminishing rapidly on the Arctic Sea, the opportunity of using the Northern Sea Route (NSR) increases correspondingly. However, the climate and presence of ice on the NSR sets additional requirements, which represent an additional investment cost for the ship owner who's potentially willing to use the NSR. These additional investment costs, mainly represented by the ice classification, may be up to 12 % higher on total ship cost, depending on ice class, see Polach, Janardanan, and Ehlers (2012). These estimates are however uncertain, as are many other specifics of operating on the NSR; the degree of ice presence, the future fee cost on the NSR, insurance and additional maintenance cost together with varying operational time on the NSR. Numerous of assessments to determine the potential cost advantage of using the NSR as a transit route have been conducted throughout the recent years. These are, however conflicting in their conclusions and a final answer to the question is therefore lacking.

Therefore, this thesis presents a decision support model (DSM) that can be used to support and assess the question of using the NSR or not based on own costs and available information. The DSM takes into account amongst others; ice conditions, the vessels parameters and its performance in ice, the operational window on the NSR, the initial investment cost of the vessel, and finally the operational and voyage costs. All these variables are changeable, and therefore the potential user of the DSM can alter them and see its effect on the calculated output, which are, amongst others: the ship merit factor (SMF), the life cycle cost (LCC) and the required freight rate (RFR).

In addition to the developed DSM, a scenario where investing in a new ice classed vessel for use on the NSR in the summer season when there is less ice, and navigating the Suez Canal Route (SCR) the remaining annual operational time is presented. Through a brief assessment on the cargo flow between East-Asia and Europe, it was decided to implement the DSM for container shipping, as this is the main traffic on the route which could benefit from the shorter distance provided by the NSR. Based on this decision, how to combine the fixed schedule of liner shipping with the uncertainty of the NSR has been discussed. Here it has been concluded that the best way to combine the two routes for liner shipping is to slow steam the NSR when the ice conditions are favourable.

Furthermore, the design requirements for ships navigating on the NSR have been reviewed in addition to the limiting parameters and constraints of the route. These and other special requirements for NSR navigation have been summarized and compared versus the open water requirements of the SCR.

In order to implement performance in ice and open water into the DSM, prediction methods for brash ice resistance, net thrust and open water resistance have been studied. These formulas, in addition to schedule, fuel, operational and voyage costs, cargo amounts and other calculations have been implemented in the DSM.

With the DSM developed, it has been evaluated through sensitivity calculations to ensure that it behaves reasonable when input parameters are altered. Moreover, two case studies have been conducted, both using the established scenario of using the NSR in addition to the SCR. In the first case study, the performance of a SCR vessel fitted with an ice class and the other requirements needed is assessed for the different ice classes of the Finnish Swedish Ice Class Rules (FISCR). In the second case study, the possibility of optimizing the design of the first case study to fit the schedule and route better, and thus yield more profit, is investigated through the DSM.

Under the given assumptions and input used, all the FSICR classed vessels are found to be more profitable using the NSR in the summer season than the same vessel without ice class navigating only the SCR. However, with the profitability declining as the ice extent and thickness grows, the dictating element on NSR profitability is the ice conditions. The 1A ice classed vessel have been found to be the best alternative of the FSICR vessels, when also taking into consideration the ice capabilities of the 1A ice class with respect to ice thickness. Results of the second case study show that having an optimized vessel for the specific route and schedule is important in order to maximize profit as the optimized 1A ice classed vessel show better performance in all calculated results and ice scenarios.

The economic advantage of using the NSR under the given scenario is however marginal. And the potential user of the NSR must therefore take into account the additional risk and uncertainty in terms of ice navigation and unforeseen expenses of using the NSR, before making the final decision. With increasing traffic over the recent years, it is well established that using the NSR is technically feasible. Nevertheless, in order to have shipping on the NSR on a regular basis, one must first and foremost have ice conditions that permit safe, economic and consistent navigation. Secondly, there must be a consistent fee system, which does not take away the benefit of the shorter distance in addition to shorter lead-time for booking NSR assistance. With these prerequisites in place, use of the NSR can be beneficial financially and in terms of reduced emissions.

Norwegian Summary

På grunn av den økte temperaturen i Arktis trekker havisen seg tilbake, noe som åpner for skipstrafikk gjennom Nordøstpassasjen eller mer kjent som Northern Sea Route (NSR). Klimaet og isen i Arktis gjør at skipene som skal navigere der må tilfredsstille høye krav. Disse kravene er i hovedsak representert i en isklasse, noe som utgjør en ekstra investeringskostnad for redere som vil bruke NSR. Forskjellige estimat antyder at ekstrakostnaden ved isklassifisering utgjør opp til 12 % høyere skipskostnad, men disse estimatene er i stor grad usikre. Denne usikkerheten gjenspeiles også i mange andre aspekter ved seiling på NSR, som for eksempel isforholdene, kostnaden som betales for å passere, operasjonstiden på NSR, og i tillegg til usikkerhet rundt de forskjellige operasjons- og driftskostnadene. Forskjellige vurderinger av NSR som snarvei mellom Europa og Øst-Asia, har blitt utført de siste årene for å svare på den eventuelle økonomiske kostnadsbesparelsen av å bruke ruten. Disse vurderingene er derimot sprikende i deres konklusjoner og spørsmålet står derfor til en viss grad fortsatt ubesvart.

I lys av dette presenterer derfor denne masteroppgaven en beslutningsstøttemodell for containerskip som kan brukes til å vurdere og støtte beslutningen om å bruke NSR eller ikke, basert på egne operasjonskostnader og tilgjengelig informasjon. Beslutningsstøttemodellen, heretter omtalt som modell, tar hensyn til isforhold, skipets parametere og dets ytelse i is med tilhørende drivstofforbruk, operasjonstid på NSR som resultat av isklasse, investeringskostnaden av skipet og dets operasjons- og driftskostnader. Gjennom resultatene fra modellen, som er skipskvalitetsfaktoren (ship merit factor), den nødvendige fraktraten og livssykluskostnaden, kan bruken ta en vurdering i tillegg til å endre parametere og se dets effekt.

I tillegg til beslutningstøttemodellen presenteres et senario hvor ett isklasset skip brukes på NSR i sommersesongen, og som bruker Suez Canal Route (SCR) den resterende delen av året. Basert på godsflyten mellom Europa og Øst-Asia ble det bestemt å utvikle modellen for containershipping, som utgjør den største trafikken mellom kontinentene. Med utgangspunkt i denne beslutningen, diskuteres det videre hvordan en kan kombinere usikkerheten rundt bruk av NSR med de faste operasjonsmønsteret i containershipping. I den sammenheng ble det fastsatt at å redusere skipets hastighet (slow-steaming) gjennom NSR, er den mest gjennomførbare metoden for å kombinere de to rutene.

Videre har spesifikasjonskrav for skip som skal navigere på NSR blitt gjennomgått i tillegg til begrensninger i designparametere. Disse og de andre spesifikasjonskravene gjeldende på NSR er blitt oppsummert og sammenlignet med kravene for skip på SCR.

For å kunne implementere skipets ytelse i is og i åpent farvann i modellen, har metoder for å forutsi ismotstand, ”net trust” og mostand i åpen farvann blitt studert. Disse metodene, samt drivstofforbruk, operasjons- og driftskostnader, lastemengder, og andre tilhørende formler har blitt implementert i modellen.

Med modellen etablert og utdypet, blir den evaluert gjennom sensitivitetsanalyser for å sikre at den gir rimelige resultater etter hvert som parametere blir endret. Videre har to studier blitt gjennomført ved bruk av modellen for det etablerte senarioet om å bruke NSR i tillegg til SCR. I det første studiet blir det evaluert hvordan et SCR-skip som oppfyller kravene til NSR vil yte i de forskjellige isklassene i de Finnish Swedish Ice Class Rules (FISCR). I det andre studiet blir det utforsket hvordan en kan forbedre designet ved å tilpasse det for ruten det skal seile, og dermed gi bedre finansiell avkastning.

Under de gitte antagelser og parametre som er brukt, vil alle isklassene av FSICR gi bedre finansiell avkastning enn et standard SCR skip som seile kun SCR. Imidlertid viser resultatene at besparelsen av bruk av NSR er sterkt avhengig av gunstige isforhold, med minkende fordel dess mer is på NSR. På bakgrunn av dette kan det fastslås at isforholdene er den faktoren som dikterer den potensielle besparelsen ved bruk av ruten. Av de forskjellige isklassene i FSICR, har isklasse type 1A blitt funnet som den mest gunstige, hvor også kapasiteten i henhold til istykkelse har blitt tatt med i vurderingen. Resultatene fra den andre studien viser at det er mye å hente på å optimalisere designet med hensyn til ruten, hvor det forbedrede isklasse-1A-skipet viser bedre ytelse for all beregnede resultater og is senarioer.

Det skal dog bemerkes at den økonomiske besparelsen ved å bruke NSR som angitt ovenfor er marginal. Potensielle brukere av NSR må derfor ta hensyn til risikoen og usikkerheten forbundet med å navigere i is og de pålydende kostnadene deretter. Med økende trafikk over de siste årene, er det ingen tvil om at det er teknisk mulig å seile NSR. I midlertidig, vil fremtidig shipping gjennom NSR på regulært basis være avhengig av først og fremst gunstige isforhold som tillater sikker, økonomisk og konsistente seilaser. Et forutsigbart avgiftssystem for ruten, som ikke fjerner besparelsen av den kortere avstanden og raskere behandlingstid for brukstillatelse, til være nødvendig. Med disse forholdene tilstede, vil bruk av NSR være gunstig både fra et økonomisk og miljømessig synspunkt.

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Nomenclature

AAC – Annual Accumulated Cost
Awf – Referring to Waterline area of bow
CPP - Controllable Pitch Propeller
DAS – Double Acting Ship
Dp – Delivered power
DSM – Decision Support Model
DSS – Decision Support System
FISCR –Finish Swedish Ice Class Rules
FPP – Fixed Pitch Propeller
H-V- Referring to ice thickness – speed performance in ice
HFO – Heavy Fuel Oil
Hm – Referring to average height of brash ice in channel
IASC - International Association of Classification Societies
IB - Icebreaker
ice – Subscript referring to ice
IMDG - International Maritime Dangerous Goods Code
IMO - International Maritime Organization
LCC – Life Cycle Cost
Lpar – Referring to length of parallel mid body on ship
MARPOL - International Convention for the Prevention of Pollution from Ships
MCR – Mean Continuous Rating
MDO – Marine Diesel Oil
MOHQ - Arctic Marine Operations Headquarters
NPV – Net Present Value
NSR – Northern Sea Route
ow – Subscript referring to open water
PC – Polar Class
Pd – Propeller diameter
RFR – Required Freight Rate
RMRS – Russian Maritime Shipping Register
SCR – Suez Canal Route
SMF –Ship Merit Factor
SOLAS – Safety of Life at Sea
TEU – Twenty-foot equivalent unit
Tnet – Referring to net thrust

Introduction

This Master Thesis touches upon several topics related to shipping on the Northern Sea Route (NSR) and the Artic Seas.

- Design requirements for NSR
- Container shipping
- Transport systems
- Profitability
- Design performance

The problem description below presents the work included in this thesis in more detail.

Problem Description

The global climate change continues to increase the marine transport in the Arctic Sea as a result of decreasing ice extends. However, the distinct conditions of Arctic Sea, such as remoteness or the lack of marine infrastructure, represent a challenge to be surpassed in order to ensure a safe and economical feasibility. Furthermore, the assessment of the parameters and their sensitivity influencing the ship design for Arctic conditions, and thereby the safety of life at sea, are of utmost importance.

Additionally, these design parameters required today and in the future for the Arctic Sea transport need to be assessed with respect to their corresponding investment. Therefore, the purpose of this work is to assess the suitability of the current ship design requirements versus the distinct regional and environmental requirements of the Arctic Sea.

Therefore, the scope of this thesis is to develop a methodology, which can be used to assess and support the decision to use the NSR or not, taking into account the encountered ice conditions and the vessels performance including the fuel consumption as well as the investment cost of an ice classed vessel fulfilling the requirements, the operational and voyage costs and the operational window of the NSR. Thereby, the varying conclusions reached in recent years, following various assessments of the NSR, can be surpassed and a clear identification of the vessels profitability in view of the NSR usage compared to the Suez Canal route can be made. Further, a review of the southern transport system and a description of an e.g. fleet, and operational profile to be combined with the NSR are to be discussed. The presentation of the findings and results, both on a general applicable level as well as highlighted through a case study shall be included.

Based on the problem description above, the first chapter of this thesis consists of a review of the earlier assessments of using the Arctic Sea as a transit route between Europe and East-Asia, or other routes where using the Arctic Sea could be beneficial. In addition, a decision support system (DSS) is described and put in context with the decision support model (DSM) develop in this thesis. Secondly, a scenario of using the NSR in combination with the Suez Canal Route (SCR) is presented briefly followed by a flowchart of the contents of the DSM.

With the background for the model and why it is needed presented, the scenario of which it is thought for is presented in more detail. With the DSM being developed of container shipping, the second chapter puts some emphasis on the specifics of container shipping and how the southern transport system can be combined with use of the NSR. Being developed for the NSR, the current state and review of requirements for the route are presented together with meteorological aspects and ice conditions.

Having presented what is required and how the conditions on the NSR are, the different aspects of designing a vessel for the route and limiting factors and constrains are discussed in chapter 3. The ice class requirements and its affect on the design are established and summarized in a table comparing the requirements and design specifics for the NSR with the ones of the SCR.

With the requirements and what vessels to navigate the NSR must be capable of established, chapter 4 therefore describes how one can predict and implement, mathematically, the performance of these vessels in ice and open water to the DSM.

Chapter 5 presents the DSM and how it works, as well as presenting the ship merit factor (SMF) for vessels that combine two routes, such as the NSR and SCR and the other calculations and formulas of the DSM. Further, a brief assessment of how the model behaves when input is altered is discussed through sensitivity calculations.

In chapter 6, with the model and how it works together with the abovementioned aspects established, a case study of using the NSR in addition to the SCR is presented. Using a SCR vessel fulfilling the requirements of the NSR, the different ice classes of FISCR have been evaluated. In addition sensitivity calculations have ben conducted. Lastly, a final second case study has been conducted to display how the DSM could be used to optimize the design through the SMF. Lastly the different assumptions, simplifications of the DSM and other aspects of navigating the NSR is discussed in greater detail in chapter 8, followed by a finalizing conclusion.

1 A Decision Support Model for Merchant Ships Operating on the Arctic Sea

With the ice diminishing rapidly on the Arctic Seas, the opportunity of using the Northern Sea Route (NSR) increases correspondingly. However, the climate and presence of ice on the NSR sets additional requirements, which represent an additional investment cost for the ship-owner who's potentially willing to use the route.

These additional investment costs, mainly represented by the ice classification, may be up to 12 % higher on total ship cost, depending on ice class, see Polach et al. (2012). These estimates are however uncertain, as are many other specifics of operating on the NSR; the degree of ice presence, the future fee cost on the NSR, insurance and additional maintenance cost together with varying operational time on the NSR.

With increasing interest over the last years, numerous assessments of the NSR have been conducted. The most in depth study was the International Northern Sea Route Program (INSROP), which from 1993 to 1999 investigated all aspects concerning increased international traffic on the NSR. The study created in total 167 reports on different subjects like; natural conditions, ice navigation, trade and commercial aspects, environmental factors, legal and political factors and so on.

The main conclusions of the INSROP program were that international commercial shipping is feasible in economic, technological and environmental terms. However, the most interesting conclusion in respect to this paper is (INSROP, 2012):

"Calculations comparing the NSR with Suez have identified several scenarios in which the NSR will be the most profitable alternative, using already suitable vessels and provided that Russia adopts a reasonable tariff policy for the route."

Secondly, INSROP was not able to identify any realistic scenarios under current market, technological or climatic conditions where building of new vessels especially for NSR transits could be more profitable than ordinary vessels to be used through Suez (INSROP, 2012).

Several years have gone since the INSROP program, and in the recent years, numerous of vessels have transited through the NSR in summer time, but shipping on a regular basis is yet to be seen. Several studies have been conducted to determine the potential cost advantage of using the NSR as a transit route: (Borgerson, 2008), (Verny & Grigentin, 2009), (Liu & Kronbak, 2010), and (Schøyen & Bråthen, 2011). It should of course be noted that the quality of these studies are, as with this one, connected to the assumptions and underlying hypothesis such as average transit speed in ice, cost of building and operating the ship, and of course the fuel cost.

Borgerson (2008) states that the variables determining the freight rates, such as the canal fees, fuel costs and other variables could be cut by as much as 20 % of a single voyage by a large container ship. On the other hand, Verny and Grigentin (2009), conclude that the costs are much higher than through Suez, while Liu and Kronbak (2010) concluded that the NSR is not economically feasible if the ice breaking fee remains at current level, but sees the NSR as competitive to the Suez if the fee lowers. Schøyen and Bråthen (2011) points out that the NSR coastal routes with vessel draught and beam limitation are a hindrance for large vessels and therefore achieve the same economies of scale in shipping as via Suez.

A overview of assessments using the Arctic seas as an alternative route, is provided by Lasserre and Pelletier (2011) in Table 1.

Table 1: Assessments of Arctic Sea Routes

Study	Aspect studied	Position
Guy (2006)	NWP summer transit	Potential profitability is uncertain given uncertainty on routes and higher costs
Aker Arctic (2006)	Container shuttle service between Iceland and Aleutians	Marginal but real profitability
Borgerson (2008)	Arctic transit in general	Very profitable because of shorter distances
Somanathan et al. (2009)	Transit using the NWP compared with Panama between Asia and the Northeast coast of North America	Present profitability is negative or marginal
Mejlænder-Larsen (2009)	Container transit using NSR compared with Suez	Potential profitability but not in the near future
Verny and Grigentin (2009)	Container transit using NSR compared with Suez	NSR is technically feasible
Liu and Kronbak (2010)	Container transit using NSR compared with Suez	Costs are about twice as high on the Northern Sea Route as on the Suez route
DNV (2010)	Europe -Asia transit year-round	NWP not profitable Year-round transit not profitable unless very high fuel prices NSR competitive for northern Asian hubs in summertime in 2030

Based on the conclusions of INSROP, this paper presents a scenario where investing in a new built vessel for use on the NSR when the conditions are favourable, while using the Suez Canal Route (SCR) on the remaining annual operational time. Based on the mentioned scenario, and the conflicting results from different assessments of the NSR, this paper presents a Decision Support Model (DSM), which can be used by shipping companies to assess the potential benefit of using the NSR using their own data and information.

The DSM takes into account ice conditions, the vessels parameters and its performance in ice, the operational window on the NSR, the initial investment cost of the vessel, and finally the operational and voyage costs. All these variables are changeable, and therefore the potential user of the DSM can alter them and see its effect on the calculated output, which are, amongst others:

- The ship merit factor (SMF)
- The life cycle cost (LCC)
- The required freight rate (RFR)

A DSM is basically only a part of a decision support system DSS, which according to Nof (2009) can be described as;

"Interactive computer-based systems that help people use computer communications, data, documents, knowledge and models to solve problems and make decisions."

DSS has developed along with the evolution of computer and information technology, and is basically systems that combine management science models and solution techniques to address complex, interrelated organization problems. DSS has a wide variety of applications, such as used by analysts in airlines to select pricing and routing, specialists uses DSS that focus on financial and simulation models, in addition to investment evaluation (Nof, 2009).

Generally a DSS is interactive, combining databases and different management science models and solutions techniques with a user interface that allows the user to ask questions and receive answers. A simple version of a DSS can be a excel spread sheet which calculates the break-even point, where the user can alter the input and see its effect (Taylor, 2007). The basic structure of a DDS could be like illustrated in Figure 1, with a database component, a modelling component and a user interface with the decision maker.

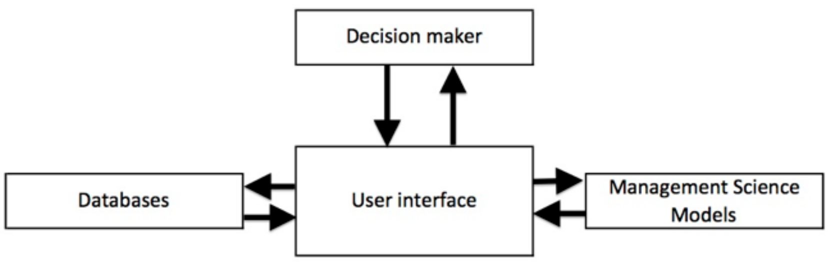


Figure 1: Structure of DSS

In addition to helping managers answer specific questions and make decisions, a DSS may be very useful in addressing "what if" questions and performing sensitivity analysis. When management science models are linked together with different databases the user can change a parameter and see what the effect will be (Taylor, 2007). Here, in this context, sensitivity on important parameters such as fuel price and ice extent etc. will be important for the user in order to find scenarios where using the NSR and investing in an ice classed vessel could be beneficial.

Mathematical and analytical models are the major component of the model-driven DSS, where the value of key variables or parameters are changed, often repeatedly to reflect potential changes in supply, costs, environment etc., which then is analysed and evaluated by the decision maker (Nof, 2009).

It is the model for a DSS that is developed in this thesis, which is written in MATLAB code, where the user first provide the needed information, such as, amongst others; the parameters of the vessel, ice conditions, operational costs and insurance in addition to schedule and route information. The model will then calculate, and display the results. See Figure 2.

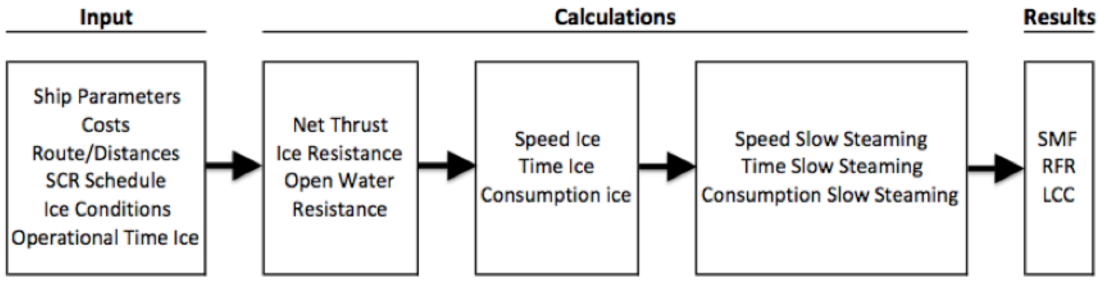


Figure 2: Flowchart of DSM

Using the SMF it can be shown qualitatively how well the design suites the transport system it is meant for and how it will perform if put in another context, such as the NSR. For example, the SMF will indicate how a design for the SCR will perform on the NSR given it fulfils the requirements. In addition the RFR and the LCC give information on the economic aspects, which is valuable for the decision maker.

The DSM can be used to assess numerous questions, in addition to the already mentioned, it could be used to assess questions such as: Under what fuel prices and market scenario using the NSR can be beneficial, what the ice conditions must be, how many trips using the NSR that must be accomplished to pay back the additional ice class investment, and as a general route comparison tool.

2 Introducing a Scenario: Using NSR in Combination with SCR

Due to the short operational time on the NSR, this paper suggests investing in vessels, which are capable of navigating on the NSR that only uses the route when the ice conditions are favourable. As the different ice classes have specific ice capabilities with respect to thickness, the respective ice classes have different operational time on the NSR as the ice increases in both extent and thickness as the operational seasons goes to an end. Due to the shorter distance between Northern Europe and Eastern Asia when using the NSR, it is suggested, that depending on the ice conditions, vessels can slow steam through the NSR, possibly saving fuel costs.

In the process of evaluating the most suitable and economic sustainable commodity to be transported along the route, the current cargo flow between the Far East and Europe has been used. In order to benefit from the potential reduction of routing by using the NSR, the route should be from Northern Europe to countries in the Far East such as China, Japan and South Korea. The main imports and exports between Europe and the Far East are machinery and transport equipment; hence this is containerized cargo (http://ec.europa.eu/trade/).

For a liner shipping company, running a container shipping service between ports in Europe and in the Far East the benefit of using the NSR is potentially large. But how to combine, and fit shipments through the NSR into the regular liner service, can be a challenging task with numerous solutions. The following alternatives assume that one operates a port-to-port service between Asia and Europe with no intermediate stops.

1. Slow steaming through NSR
2. Normal speed

Alternative 1 is about slow steaming (reducing vessel speed) through the NSR in the navigational season, and thereby utilizing the shorter distance. By doing so, the operator will consume less fuel by steaming slower, as speed and consumption is directly connected as Figure 3 presents. Slow steaming is a usual strategy for ship operators to save costs in market lows, in addition to decreasing transport capacity and emissions (Cariou, 2011) (Stopford, 2003). Using this alternative, the operator can fit the use of the NSR without altering the existing schedule.

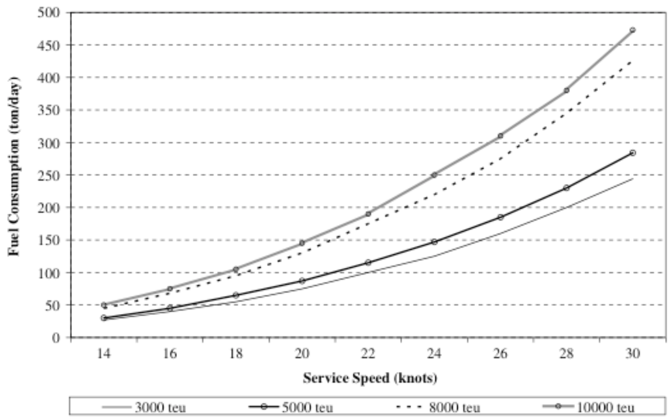


Figure 3: Consumption as function of speed (Nottebom, 2011)

The second alternative is to go through the NSR at regular speed. That way one could use the NSR as a way to increase cargo flow due to the shorter distance, and thus increase the round-trip capacity. In periods with high demand, this alternative could be used. Although, fitting alternative two into the regular operation will be more demanding than slow steaming as in alternative one.

In addition to fitting the schedule, the potential operator using the NSR in combination with the southern routes must find a suitable mix of vessel types to use. The degree of ice capability must be decided, and choosing the correct ice class could mean profitability or not. Corresponding to the choice of ice class, the cost of IB support must be evaluated, as with high icebreaking capability, the lower the IB fee and the longer navigational season on the NSR (Liu & Kronbak, 2010).

According to Polach et al. (2012), who refers to Nowacki (1985), the SMF refers to hydrodynamic aspects and is only valid if ship revenues are equal. Additionally, as discussed above, combining the NSR with the SCR is easier when slow steaming the NSR. Therefore the calculations of the framework are based on a fixed schedule, and the number of trips and thus revenue is equal independently of choice of route.

2.1 Liner Shipping and the Southern Transport System

To develop and to discuss a feasible transport system using the NSR to be combined with the southern routes using the Suez channel one must first have knowledge of how the southern system work as it builds the premises of the new system that must be adapted to the existing system. Here emphasis will be laid on liner shipping, although perhaps a hard combination to be combined with the NSR due to the uncertainty in ice conditions, it is in liner shipping market such as container shipping usage of the NSR could have its biggest advantages

According to Stopford (2003) shipping companies meets their costumer's needs, which include a range of factors, of which the most important are: Price, speed, reliability and security. All of these are affected by the choice of route, thus it is clear that these factors must be assessed when looking into using the NSR in combination with the southern routes. The degree of presences of ice alone will affect all these factors. Shipping is of course only a part of a larger transport system build up of roads, railways, airfreight etc. which also to some degree competes with each other, and there are large support systems running the business such as ports etc. These support systems will, however not be dealt with in this thesis.

Liner shipping is characterized by offering a regular transport service for cargoes that are too small to fill a single ship. Due to the more complex nature of these small and many single packages, liner shipping requires more administration compared to bulk shipping. According to Stopford (2003) the liner operator must be able to:

- *offer a regular service for many small cargo consignments and process the associated mass of paperwork;*
- *charge individual consignments on a fixed tariff basis that yields an overall profit—not an easy task when many thousands of consignments must be processed each week;*
- *load the cargo/container into the ship in a way that ensures that it is accessible for discharge (bearing in mind that the ship will call at many ports) and that the ship is 'stable' and 'in trim';*
- *run the service to a fixed schedule while allowing for all the normal delays— arising from adverse weather, breakdowns, strikes, etc.; and*
- *plan tonnage availability to service the trades, including the repair and maintenance of existing vessels, the construction of new vessels and the chartering-in of additional vessels to meet cyclical requirements, and to supplement the company's fleet of owned vessels.*

As one can understand from the characteristics above, combining the strict and highly planned schedule of the liner shipping companies with the uncertainty of the NSR where the risk of delay caused by presence of ice, etc. can be demanding.

The east-west routes dominate the liner business, and have grown rapidly over the last 20 years, and according to Verny and Grigentin (2009) the United Nations have estimated that the Asia-Europe container market will grow at an annual rate of 5-6 % between 2008 and 2015. Other studies anticipate that over a period from 2005 to 2030, the volume of containerized traffic between Asia – Europe will increase by more than 600 % (Verny & Grigentin, 2009). With the anticipated growth in traffic as described above, it is obvious that the Suez Canal can suffer from congestion problems in the future, and according to Verny and Grigentin (2009) it already is.

The Suez Canal offers a significant shortcut compared with rounding Cape of Good Hope when navigating East-West. The canal has been enlarged numerous of times, and after the latest expansion in 2010, it can accommodate all the container vessels in the world with a draught limitation of 20 meter (www.suezcanal.gov.eg). Ships transit the Suez Canal in three convoys daily, with two convoys southbound and one northbound. In 2011, a total of 17 799 passed through the canal, paying in average $290 000 per vessel (www.suezcanal.gov.eg). According to Nottebom (2011) the fees are likely to rise in the period 2015 to 2020, and so will the waiting time due to capacity constraints. On average, vessels use 12 -16 hours to transit the canal, though this does not include waiting time. A summarizing table by (Omre, 2012) of the differences for the Suez and NSR is presented in Table 2.

Table 2: Route comparison

	NSR	Suez	Comments
Distance [nm]	8030	10553	Rotterdam-Shanghai
	7280	11180	Rotterdam-Yokohama
Time [days]	Depends on the ice conditions	18,3* 19,4*	*With an average speed of 24 knots
Uncertainties	Ice and weather conditions, Russian regulations	Piracy	Rules of the Russian administration are affected by variations
Transit notice	4 months	48 hours	
Insurance	No model exists	Yes	
Probability of delays	High	Low	
Max draught	13 m	20.1 m	
Max width	30 m	50 m	
Infrastructure	Not sufficient	Good	

Many of the operators are apart of the Far East Freight Conference system, which affects the price on the route (Stopford, 2003). The freight rates for Asia – Europe according to Rodrigue (2012) is shown in Figure 4. There is a large freight imbalance between Asia – Europe, and according to Verny and Grigentin (2009) there is about two twenty foot equivalent unit (TEU)s leaving Asia for every TEU leaving Europe. As can bee seen in Figure 4, the price of sending a TEU between Europe and Asia is heavily dependent on direction. According to Verny (2007), the cost of sending a container between two fixed ports was on average three times higher for routes from Asia to Europe than the inverse. Profitability in container shipping is not the best compared with other industries, with an average return on asset from 1 to 8 % in the first half of the 1990`s (Stopford, 2003). It could therefore be that shipping companies will be reluctant to invest in high-risk NSR projects.

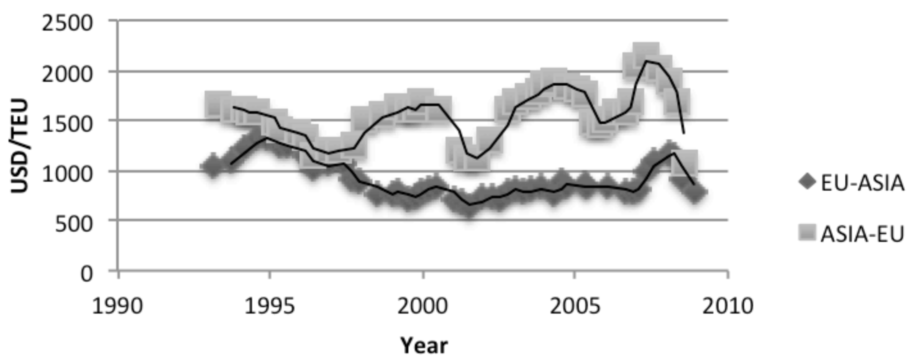


Figure 4: Freight rates

The typical round voyage time is sixty-three days, and requires nine ships to provide a weekly port call, which includes calling at four European ports and four or five Asian ports (Stopford, 2003). Increasing the speed will reduce the round time, and thus the number of needed vessels. In addition, reducing the number of port calls will have the same effect. How to combine the speed and port call with the NSR is a difficult question to solve with large cost implications. For the liner fleet, the speed increases with the size of the vessels, as the larger the vessel, the longer the haul (Stopford, 2003).

Economies of scale offer cheaper transport on many routes, though constraints or lack of cargo volume requires use of small ships on some routes (Stopford, 2003). According to Wijnolst and Wergeland (2009), which divide container shipping into global container shipping and container feeder, global container shipping is constantly pursuing economies of scale, and at the same time tailoring towards the door to door needs of the costumer. Based on the above, it is evident that for a container vessel that operates on the Far East trade using the NSR economies of scale will be of importance, thus the ship size is important.

2.2 Review of Current Conditions on the NSR

The Northern Sea Route (NSR) is defined as the different fairways going from Novaya Zemlya in the west to the Bering Strait in the east as presented in Figure 5. The length of the route depends on the ice conditions and the choice of different stretches of the route, but is generally considered as 2100 to 2900 nautical miles long. The Russians have claimed to own the route and have controlled the traffic since the beginning of the 20th century. The route was closed for international shipping when the Soviet Union was formed in 1922 and remained closed till the breakup of the union in 1991. The first commercial transit was completed in 2009.

Figure 5: The NSR

Today there is a growing interest in the NSR as a transit route mainly because the distance between Northern Europe and Northeast Asia can be reduced with as much as 70 % compared to the traditionally route through the Suez Canal. The presence of thick ice has been the main reason for not considering this pathway as an option, however as the ice continues to diminish the economic potential is becoming larger. The distance and transit time between Kirkenes in Norway and three large Asian ports can be found in Table 3 based on a ship sailing in September when the ice cover is almost gone or very thin. The entire NSR is only open to commercial shipping in the navigation season from early August to late November, though as ice decreases this window in expected to increase correspondingly.

Table 3: Distance and transit time when using NSR (Tschudi, 2010)

	Via Suez Canal			Through Northern Sea Route			
Destination	Distance Nm.	Speed Knots	Days	Distance Nm.	Speed Knots	Days	Days Saved
Shanghai,China*	12050	14	37	6500	12.9	21*	-16
Busan, Korea	12400	14	38	6050	12.9	19.5	-18.5
Yokohama, Japan	12730	14	39	5750	12.9	18.5	-20.6

* Based on actual voyage performed by M/V Nordic Barents from Kirkenes to Lianyungang (China), September 2010

Only recently have companies begun to find the route interesting, as the receding polar ice cap has opened paths further offshore that allows larger ships with deeper drafts to make the journey. 2009 was marketed as a test year for commercial ships sailing the entire NSR from Europe to Asia, and two vessels from Beluga Shipping Group sailed on the NSR as a part of a small convoy escorted by a Russian nuclear-powered icebreaker (IB). In 2010 the traffic increased and 8 vessels completed the journey.

In 2011, 34 vessels went through the NSR and the sailing season was extended by a month. Among these ships was the Panamax-class tanker STI Heritage that set a speed record with an average speed of 14 knots, using 6.5 days on the NSR in total.

During the navigation season all shipping on the NSR is under the control of the Arctic Marine Operations Headquarters (MOHQs). Having at their disposal data from aircraft ice reconnaissance and ice patrol, as well as ice hydro meteorological forecasts, the MOHQs determines dates of beginning and termination of navigation on different route stretches. They also provide optimum routes for shipping; icebreaker support and aircraft ice reconnaissance support. To enter the route and get the support from MOHQs, everyone has to pay a certain fee. The fee depends on different criterions; time of year, navigation on the entire path or parts of the NSR and the ship size. No model for calculating the fee exists; so far the amount has been established through negotiation (Dodd, 1985).

To make shipping in the NSR a commercial success it is important that the fees don't erase the advantages of the reduced transit time. The large fees have been looked upon by many as one of the major obstacles of making the NSR into a commercial pathway. Currently, the fee is negotiable down to 5 USD/ton according to Erikstad and Ehlers (2012). The manager of Rosatomflot, stated in 2010 at an international maritime conference that the fee, in the future, would be slightly above the Suez Canal rate (Vanebo, 2011).

The Russian Maritime Authorities have listed several requirements for the design, equipment and supplies of vessels navigation the Northern Sea Route (USSR, 1990). They aim to take into account the difficult and hazardous conditions of the area and prevent pollution of the marine environment and of the northern coast of Russia. The lowest allowed ice class for navigation on the NSR is LU4 (ice 4) of the Russian ice rules or equivalent of other classification societies, but the lower ice class of LU3 (ice 3) may be permitted as an exception in the summer navigation period (USSR, 1990). The vessels navigating the Northern Sea Route must have fulfilled several requirements concerning areas such as (USSR, 1990):

- The hull of the vessel
- Machinery requirements
- Systems and devices
- Stability requirements
- Navigation and communication equipment
- Provisions and emergency facilities.

Other statutory documents that regulate the traffic on the Northern Sea route are according to Juurmaa (2006):

- *" Guide for Navigation through the Northern Sea Route"*
- *"Regulations for Navigation on the Seaways of the Northern Sea Route"*
- *"Regulations for Icebreaker - Assisted Pilotage of Vessels on the NSR"*

To get a permit to sail the NSR the operator must apply 4 months in advance, and vessels are subject for inspections before commencing on the route. The inspectors evaluate the ice worthiness of the ship to estimate how much escort the ship needs from icebreakers and to clarify that all other requirements are satisfied. If the ship is approved the MOHQs will schedule a date and route based on the capabilities of the ship and the availability of icebreakers (Liu & Kronbak, 2010).

To assist merchant vessels and to maintain traffic flow on the NSR the icebreaking fleet is of outmost importance. The parameters of the assisting fleet together with its capabilities are directly affecting the traffic on the NSR. Currently there are both diesel-electric and nuclear powered icebreakers operating on the NSR. The nuclear icebreakers are highly capable and have icebreaking capability of up to 2-meter ice thickness with beams from 27 to 30 meter and propulsion power up to 54 MW.

2.3 Review of Meteorological Conditions and its Affect on Navigation

In addition to ice, navigation is among others affected by wind, air temperatures and visibility. Polar stations are the main regular data source for these meteorological data but they do not always reflect meteorological conditions on the NSR. There are three different climate areas along the NSR; the Atlantic area, the Siberian area and the Pacific area, which weather conditions, are summarized in Table 4, where the summer characteristics are the most interesting for the scenario here.

Table 4: Meteorological characteristics for NSR areas (Dodd, 1985)

Area	Winter	Summer
Atlantic	Low atmospheric pressure and disturbed weather	Frequent fog and rain
Siberian	Colder air temperatures than in surrounding areas	Temperatures rises considerably in the southern parts, remains cold in northern parts
Pacific	Higher temperatures, greater wind strength and more rain than surrounding areas	Lowest atmospheric pressure on the NSR, considerable air temperature amplitudes. Frequent fogs in southern parts

Throughout the year hazardous meteorological phenomena may occur on the NSR. Strong winds often appear during the winter, while in the summer fog can worsen the horizontal visibility to dangerous limits. In the Arctic Sea the levels of the hazardous weather phenomena are as listed in Table 5.

Table 5: Hazardous weather along the NSR (Dodd, 1985)

Hazardous	Very hazardous
Wind speed of 15 m/s and more	Wind speed of 35 m/s and more
Fog, snowstorm or rain reducing the visibility to 50-500m	Thick fog, snowstorm or rain reducing the visibility to 50m or less
Sticking of melting snow with a layer thickness of 11mm and more	Intensive sticking of melting snow with a layer thickness of 35mm and more
Slow icing with ice accumulation rate of 0,6 cm per hour and more	Very fast icing with ice accumulation rate 1,4 cm per hour and more

The conditions mentioned in Table 5 may appear fast and are sometimes difficult to predict. To avoid the hazardous weather conditions in the summer season, ships often have to change the course, leading to a less optimal route.

The Arctic sea ice extent has been declining for the past five decades together with the thickness of the sea ice cover (AMSA, 2009). Based on such measurements, Erikstad and Ehlers (2012) have estimated current and future operational times on the NSR for different ice classes as presented in Figure 6.

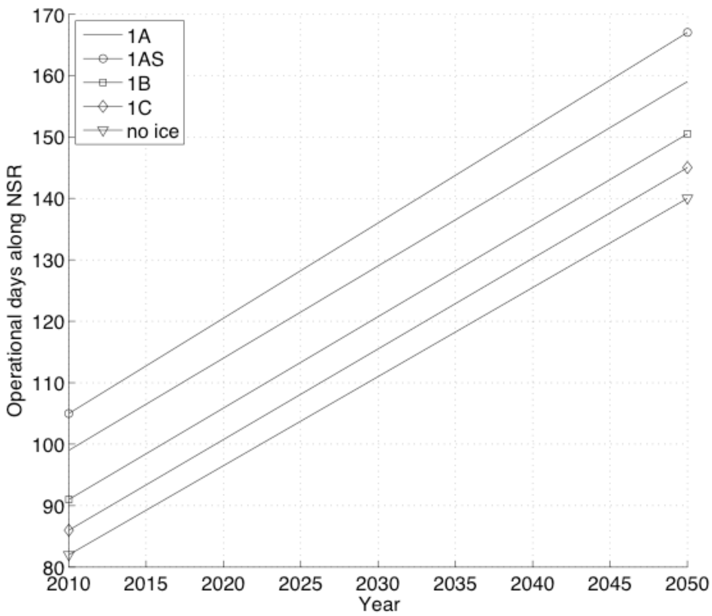


Figure 6: Current and predicted operational days along NSR for different ice classes (Erikstad & Ehlers, 2012)

Several Global Climate Models have been used to simulate the decline in sea ice cover on the Arctic Ocean. Perhaps one of the most interesting findings in these simulations is that none of them indicate that the winter sea ice cover will disappear during this century (AMSA, 2009). With this in mind it is clear that all year transport in the Arctic region will remain a challenge in foreseeable future.

The maximum extent of sea ice is found in March, while the minimum is found in September, as presented in Figure 7. From an operational view, the season is currently short and varies every year, and stretches from late July to mid October. At the end of the melting season (September), usually only the multi-year ice at the centre of the Arctic Ocean remains un-melted (Kon, 2001).

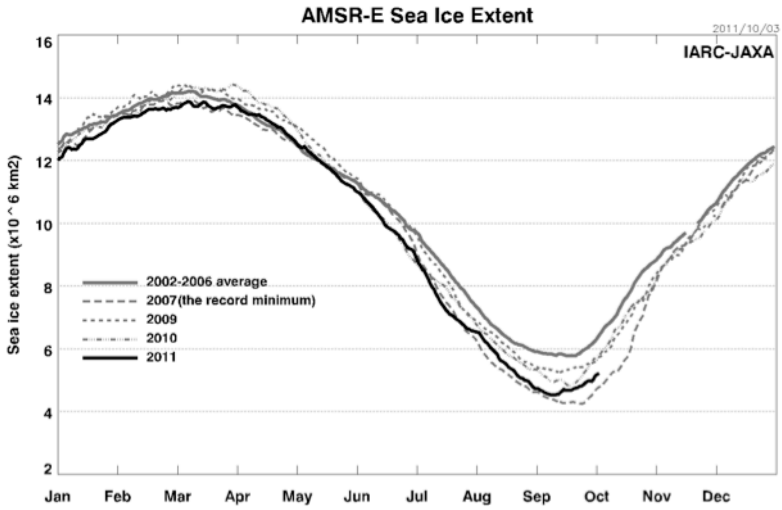


Figure 7: Sea ice extent in the Arctic Ocean (downloaded from: www.ijis.iarc.uaf.edu)

One of the dangerous situations that can occur is rapidly ice aggregation on the ships structure, which is known as icing. Icing is a phenomenon that occurs due to sea spray blown off the sea freezing on contact with the vessel. If the ice formed on the ships structure is not removed but allowed to grow it may affect the stability of the vessel. Heating of important equipment can be a solution to prevent icing, but mostly the best solution to prevent icing is protection in form of covering with forecastles, etc. (Riska, 2011a).

In areas where the sea is ice covered the problem of icing is less than when there is no ice as the ice cover prevents water from being blown up in the air. With a decrease of the ice extent the risk of icing might grow in the future. Icing will affect a container vessel heavily because of the topside cargo, which is exposed to sea spray, particularly in the bow section of the vessel. Due to the stacking of topside containers, it will also become more difficult to remove ice, in addition ice could impose difficulties in cargo handling as pointed out by DNV (2009). Another aspect is that the topside cargo is located high above the metacentre of the vessel, resulting in larger impact on the stability of the vessel if the topside cargo becomes packed with ice. The designers should therefore have this in mind

With the current ice conditions and cold climate, it is clear that vessels, which are to navigate the route, should be specially designed for the purpose, now and in the future. Therefore, the following chapter aims to provide a general overview of the technologies and design aspects of ice navigating vessels to potentially be implemented in a new build for the scenario used in the DSM.

3 Technology and Design Aspects of Ice Going Ships

Most of the literature available on the design and technology of ice navigating vessels are intended for icebreakers and design of such. Particularly the hull design of icebreakers, with low stem angles and pronounced flare of the bow section is investigated in great detail. Nevertheless, the emphasis in this paper will be on merchant ice going vessels, although many of their features originate from icebreaker design. For details concerning icebreaker design, valuable information is provided by; (AkerArctic, 2009); (Riska, 2011a); (Kon, 2001), which the following section uses parts from. In addition, a good overview of important ice design features with emphasis on icebreakers is presented in Appendix G as provided by Sodhi (1995).

Icebreakers as well as merchant vessels that operate in ice must perform well in two conflicting operating modes, which is open water and ice. Therefore the hull form often becomes a compromise between minimum ice resistance, maximum manoeuvrability, low water resistance and acceptable behaviour in open water.

Ship design begins with defining the tasks that the ship must perform (Riska, 2011b). The specification of a vessel describes the performance required and to fulfil these requirements it is essential to understand how ice is acting on a ship as it forms the basis for designing ships for ice (Riska, 2011a).

Particularly the bow section of a vessel for navigation in ice is important, as it very much decides the resistance and performance in ice and open water. However, a bow for icebreaking and open water are quite different, and an icebreaking bow performs poorly in open water and vice versa. Therefore, the designer must weight the amount of ice features versus open water features in terms of design with respect to the time spent in the respective conditions, as Lamb (2004) describes;

"The choice of ice capabilities to be incorporated in the design of a merchant ship depends on the amount of time spent in ice-covered water relative to open water, the ice conditions on the transportation service route, and on the availability and associated costs of icebreaker escort service on specific routes."

For designs with low ice capability requirements because the operation is limited to thin ice conditions, it is sufficient to design the hull shape based on open water performance and in strength issues follow the rules of classification societies or other regulatory bodies (Riska, 2011a). In research for hull form design for icebreaking tankers, Kim (2006) states that:

"To be commercially competitive, the design has to be as close as possible to conventional commercial practice, but with sufficient margins of power and strength to provide safe and predictable services for clients."

For merchant vessels that operate mostly in broken ice (brash ice) the breaking bow is often not necessary. One therefore uses a normal bulbous bow too have good open water performance. The perception of the bulbous bow for ice is mixed, and it is clearly an issue with specifying what the vessel is intended to do. Lamb (2004) states that the bulbous bow is not well suited for ice capable vessels, while Riska (2011a) states that the bulbous bow is not a handicap if the vessel is not intended to break ice because brash ice behaves like a liquid.

When turning in ice, the aft part of the hull is exposed to forces due to ice pressure. It is therefore important to have rounded stern shoulders that break ice in bending when turning (Riska, 2011a). This is potentially a problem for merchant vessels where the hull shape most often is formed to accommodate cargo; as a result, the turning ability of merchant vessels in ice is often low.

Not only the time spent in ice versus time in open water affects the design, the specific ice conditions on the planned route must be taken into consideration. Hence, for vessels that are intended to operate in heavy ice conditions, the design of the ship hull is based on taking the ice action more explicitly into account as Paik and Thayamballi (2007) states;

"The ice thickness and related pressures will be an important factor in the design of vessels for ice"

Predictions of ice conditions can be found from historical information and a way of using the ice information is to use a probabilistic measure of ice cover extent and concentration, as shown in Figure 8. This can then be evaluated against the capabilities of the chosen ice-class (Lamb, 2004).

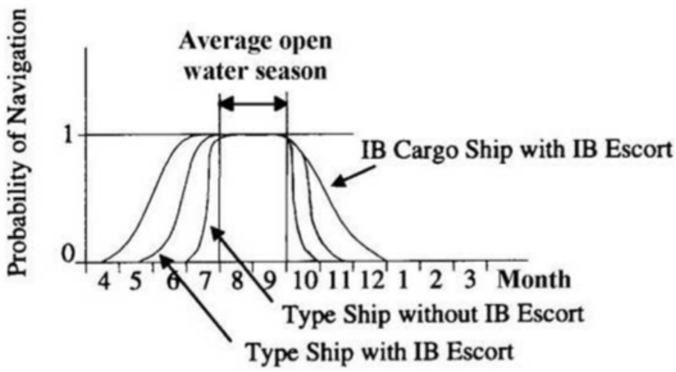


Figure 8: Probabilistic shipping season and ship capability (Lamb, 2004)

The most important feature which decides the ice capabilities, is the ice class, therefore the selection of ice class should be made with the considerations of ice conditions, operational requirements and cost (Su, Riska, & Moan, 2011).

3.1 Requirements and Ice Class Rules

The classification societies have their own ice class rules, which cover technical standards that must be fulfilled for the respective ice classes. These mainly covers the strengthening of the hull, rudder, propeller and shaft too account for the forces resulting from ice impact. Some also takes performance in ice into account, which can be specific requirements for different ice conditions, such as the Finnish-Swedish Ice Class Rules (FSICR). The ice class rules define several different ice classes depending on the severity of ice conditions. In addition to the national ice class rules, there are national rules, such as the Finnish and Swedish, Canadian. The national requirements often overlap with the ice class rules of the classification societies (Juurmaa, 2006).

At present there are three main sets of ice class rules. These are; FSICR, the Russian Maritime Register of Shipping (RMRS) ice rules and the unified Polar Class (PC) of the International Association of Classification Societies (IASC) (Riska, 2011a). The Finnish-Swedish ice class rules have been adopted by the majority of classification societies except RMRS, and have been described as the industry standard for first year ice, even though they are only intended for the Baltic (Riska, 2011a).

FSICR are intended for ships that navigate in the Baltic area, which follows the operational practice used there, and the ice class rules have performance criteria for each ice class. The rules are based on a system of icebreaker support, and the vessels pay fairway dues dependent on their ice class. Vessels with high ice class pay a lower fairway due than those with low ice class, as they need less icebreaker support (ideally). The design point in the FSICR is the elastic limit, and the equations for the scantlings have been modified over the years to reach an acceptable damage frequency (Riska, 2011a). The FSICR of 2008 ice classes are as follows, (FSICR, 2008):

- Ice Class 1A Super, ships whose structural strength in essential areas affecting their ability to navigate in ice essentially exceeds the requirements of ice class IA and which as regards hull form and engine output are capable of navigation under difficult ice conditions. The maximum level ice thickness is 1.0 meter.

- Ice Class 1A, 1B or 1C according to ice strengthening and engine output, ships which meet the requirements for navigation in ice as regards structural strength and engine output and are strengthened for navigation in ice. The maximum level ice thickness is 0.8, 0.6, and 0.4 meter respectively.

The RMRS ice class rules have nine different ice classes, and additionally four ice classes for icebreakers. Like the FSICR ice class rules, the RMRS consists of three parts, which are hull, machinery and power requirements. The power requirements are corresponding with the ice class used for the Baltic. However, the design point is a bit different, where the RMRS allows full plastic response for the plating and framing, while the limit for stringers and web frames is yield (Riska, 2011a). The RMRS ice classes are shown in Appendix E.

Because of the large differences between the ice class rule from the different classification societies the International Association of Classification Societies (IACS) introduced the Polar class. The requirements for Polar Ships apply to ships constructed of steel for navigation in ice-manifested polar waters, except icebreakers (IACS, 2011). There are seven polar classes in the IACS ice rules; these are described in Appendix E. The design point for the polar classes is based on plastic structural limit and the return period of the loads causing response up to the limit is one year, while machinery rules are based on FSICR (Riska, 2011a).

As already mentioned, most of the classification societies have adopted the Finnish-Swedish ice class rules, as a result of this; many of the ice classes are equivalent as presented in Appendix E. The different ice classes make it difficult to choose an ice class solely on the class descriptions. The ice conditions and the required safety level must in principle set the ice class that a ship should have, it is also clear that the maritime authorities where the vessel is to operate should be considered (Riska, 2011a).

When strengthening a vessel to operate in ice this primarily involves an increase in plate thickness and frame scantlings. The strengthened areas of the hull can be seen in Figure 9, as according to FSICR (2008).

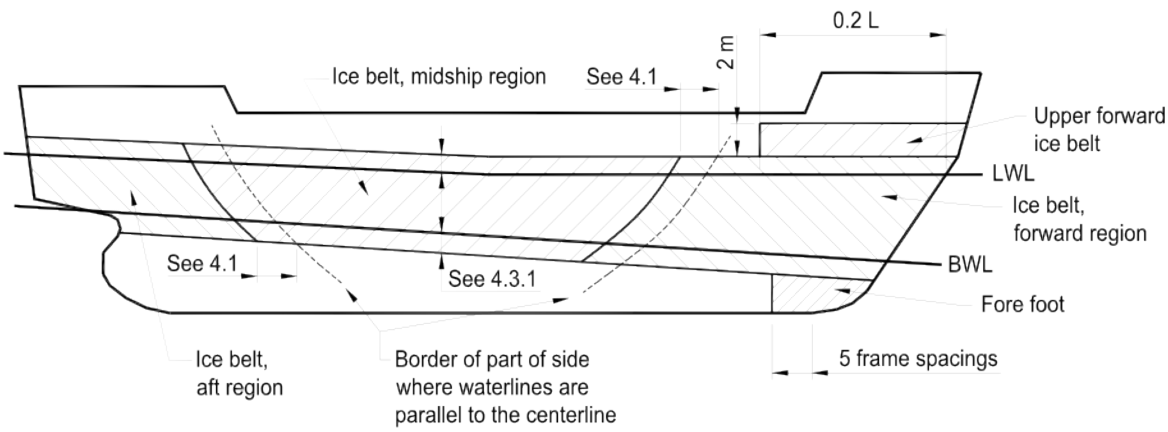


Figure 9: Regions with ice strengthening (FSICR, 2008)

The result of the hull strengthening is a higher steel weight, thus the payload compared to a similar vessel without ice strengthening becomes less. As a rough estimate, the influence of ice strengthening can according to Schneekluth and V (2007) be estimated as shown in Table 6:

Table 6: Influence on steel weight of ice strengthening (Schneekluth & V, 2007)

Germanisher Lloyd	E	E1	E2	E3	E4	Polar icebreaker
FISCR		1C	1B	1A	1AS	
Add % in hull steel weight	2	4	8	13	16	Up to 180

According to Polach et al. (2012), who investigated the weight and cost of different ice classes in FISCR by dimensioning a panel, concluded that by fitting ice class 1B or 1C, the excessive weight and cost would increase by 7 % and 11% compared to a non ice classed vessel, respectively. Also with respect to the different ice class systems there are large differences with regards to steel weight on ice classes that are supposed to equivalent to each other, see R. Bridges (2005). The ice class rules also also sets requirements to the propulsion power of the vessels, which also contribute to increase the weight of the vessel due to heavier machinery, shafts, etc. One can on the background of the numbers above conclude that the choice of ice class is not indifferent with respect to both weight and cost, and the choice of ice class should therefore be assessed properly.

Because of the cold weather the ship in areas with ice, the vessel needs to be winterized in addition to the ice classification. Riska (2011b) describes:

" Winterization refers to those design aspects that are influenced by cold water or ice cover."

Basically winterization is about dealing with problems such as icing, freezing of ballast water, etc. Det Norske Veritas (DNV), have as the first classification society established a set of notations in addition to the ice classes (Veritas, 2008). These include requirements for maintaining safety and vessel operability in cold conditions that are as follows:

- Winterized Basic
  For ships operating in cold climates for limited periods, when there is a risk of icing.

- Winterized Cold
  For ships with Baltic ice class or have the lighter polar class notations operating in cold climates for longer periods.

- Winterized Arctic
  For vessels with higher ice class notations, including additional requirements to reduce the consequences of a possible accident, operating in harsh Arctic environments for longer periods of time.

Ice classed vessels must as in addition to the ice class and winterization aspects follow the maritime safety rules and standards as normal open water vessel must. The requirements for the design of vessels navigating the NSR specifically state that the following documents must be in order (USSR, 1990):

- *"In the course of a vessel inspection. the master (owner of the vessel) is required to provide the Inspector with all necessary information, indicating which parts of the Requirements the vessel does not comply with, together with all vessel's documents, including the certificate of Seaworthiness of the vessel, if it is provided for by the national requirements, a Certificate of Classification, and' international certificates that confirm that requirements of the Convention on the Safety of Life at Sea (SOLAS – 74/78), Convention on the Prevention of Pollution from Ships (MARPOL - 73/78), Convention on Load Line (1966), as well as of IMO Codes on safety, design and equipment for special* *types of vessels (nuclear-powered vessels, chemical carriers, gas carries and so forth) have been satisfied."*

The SOLAS convention specifies the minimum safety standards for construction, machinery, equipment and operation of merchant ships. Although the SOLAS regulations are widely accepted, they are not specifically designed for ships intended for arctic operation. The AMSA (2009) report addresses the need for reviewing the *Maritime Dangerous Goods (IMDG) Code* under chapter V of SOLAS*:*

"The IMDG Code may need to be reviewed for the purpose of identifying any dangerous goods that may be affected by extremely low temperature during transportation in the Arctic."

As pointed out by AMSA, the low temperatures along the route may affect the cargo transported along the NSR. For a container vessel this might mean that not all types of cargo can be transported and thus setting restrictions to what types of cargo that can be transported in containers. A solution can be to have heated containers, but then there will be an extra cost that needs to be taken into consideration

The not mandatory IMO Guidelines for operation in Arctic ice-covered waters have several listings concerning the design of vessels for operation in the Arctic which includes construction provisions, equipment, operation and environmental protection and damage control (IMO, 2002). Although the Arctic Guidelines have been criticized for various deficiencies, they include a needed suggestion to harmonize the ice classes into Polar Class of ships into seven categories to intended ship operations and the level of ice in the area (AMSA, 2009).

The vessel specifications are dependent on the choice of the route and the related ice conditions. Dependent on future ice conditions, a potential stakeholder may risk having an either over specified vessel or a vessel with too low capabilities with economic consequences thereafter. Summarizing much of the discussed requirements of ship design for the NSR as discussed above, a list of different ship specific aspects that must be considered when evaluating transport through the Arctic Sea is presented in Table 7. For the purpose of showing what parts of the vessel that will be affected by ice classification or regular open water regulations different notations have been used where a star (*) represents that it must be according to ice class regulations, minus (-) means according to open water regulations, and plus (+) represents according to special NSR requirements. Table 7 is meant to be indicative but not exhaustive.

Table 7: Ship Specific aspects for the NSR

			NSR vessel	Suez vessel	Comments
FUNCTION	Structure	Hull,poop, forcastle, deckhouse	-	-	Designed with ice navigation in mind, features can be ice breaking bow, ice knife at rudder if using traditional rudder, sheltered forcastle to prevent icing and a deckhouse with proper view for close ice navigation
	Crew facilities	Crew spaces, service spaces, stairs and corridores	-	-	Additional insulation of superstructure and crew area should be implemented. Crew areas such as cabins should be placed above deck to minimize vibrations and noise when navigating in ice.
	Machinery	Engine and pump rooms, engine casing, funnel, steering and thrusters	*	-	Inlets for engine cooling must be placed far stern
	Tanks	Fuel & lube oil, water and sewage, ballast and voids	*	-	Additional fuel capacity with corresponding lube etc.. Waste and bilge water collecting tanks with capacity for 30-day navigation. Or cleaning system for sewage and domestic water. Ballast system must be heated to prevent freezing.
	Comfort systems	Air condition, water and sewage	+	-	Addional heating
	Outdoor decks	Mooring, lifeboats, etc	+	-	
	Cargo spaces	Holds	-	-	
	Cargo handling	Hatches & ramps, cranes, pumps,	-	-	Must be designed to function in low temperatures and have special features to account for icing
	Cargo Treatment	Ventilation, Heating and cooling, pressurizing	-	-	
	Power - speed		*	-	Ice classification sets minimum power requirements
FORM	Length		unlimited	unlimited	Dimensions are dependent on ice conditions for NSR vessel
	Breath		30 m	50 m	
	Depth		13 m	20.1 m	
	Height		unlimited	68 m	
	Trim and stability		+	-	Stability must account for ice accretion and there are additional trim requirements for ice classification
SPEED	Resistance		*	-	The power requirements according to ice class is made to satisfy performance criteria
	Propulsion		*	-	Ice classification regulates propeller design and material
	Hull Structure		*	-	Hull structure must be strengthened according to ice classificaton
	Machinery		-	-	Machinery must to designed according to ice classification
	Safety		*	-	Additional safety measures should be taken to account for navigation in ice and cold climate

Having established the design alternatives and requirements of navigating the NSR, the next step in terms of the DSM is to look at how these vessels perform in ice and open water and how this could be implemented.

4 Performance Prediction

In order to incorporate the performance in ice and open water into the DSM, with the correct resulting costs, methods of predicting performance and resistance in open water and ice have been investigated. In addition, a brief overview of level ice breaking is included, in order to understand the resistance applicable to the supporting icebreakers, which is an important part of navigating on the NSR.

4.1 Level ice

Where for open water vessels the design speed is specified in the building contract, the performance in ice for icebreaking vessels is often specified with minimum speed in a given thickness. It is therefore important to be able to predict the performance of the vessel in ice. The performance is usually measured by ice thickness-velocity curve (h-v curve), which is usually is determined in the tests. An example of an h-v curve is given in Figure 10. Ice resistance can be estimated from model testing, using experience from ships in service, or estimated by analytic formulas. A reliable way of estimating resistance is by model testing in ice basins, but these tests are time and capital intensive (Lindqvist, 1989).

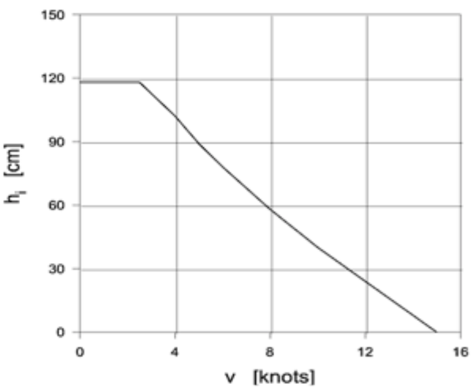


Figure 10: Example of h-v curve (Riska, 2011b)

Several ice resistance formulas have been developed throughout the years; Jones (2004) describes some of them. The early research on level ice resistance was usually carried out based on the break-displace process (Su, Riska, & Moan, 2010). According to Riska (2011b), the published ice resistance measurements are based on the assumption that open water resistance and ice resistance can be separated and superimposed to obtain the total resistance R_T, as shown in Equation 1.

Equation 1: Total Resistance in ice

$$R_T = R_{OW} + R_I$$

Where R_T is the total resistance, Row is the open water resistance and R_I is the ice resistance. The open water part is usually very small in level ice conditions. Further the ice resistance can be divided into three parts as displayed in Equation 2.

Equation 2: Components of ice resistance

$$R_I = R_B + R_S + R_F$$

Where the components are breaking, submergence and friction, respectively (Kaj Riska, 1997). As a tool for predicting ice resistance in level ice for design purposes (Lindqvist, 1989) presented a formula that take into account the shape of the hull. Later, formulas such as the one of Riska, Wilhelmson, Eglund, and Leiviska (1997), which is used to calculate the minimum power requirements in the FISCR, have built on amongst others Lindqvist's formula (Riska et al., 1997).

4.2 Channel Resistance

Merchant vessels, or other vessels, which does not break ice themselves, experience a different resistance than level ice resistance when navigating in channels with broken ice (brash ice). This type of resistance is referred to as channel resistance, which arises from displacing brash ice present in the channel both down and sideways. Riska et al. (1997) claims that as brash is left to freeze, a consolidated layer of ice is created on top of the brash ice, therefore channel resistance is consisting of two parts; one due to the brash ice, and one due to the consolidated layer. Different formulas for estimating brash ice resistance exist, and one of the frequent referred to, is the one of Mellor (1980), which investigated the properties of brash ice and brash ice resistance. Riska et al. (1997) composes a speed dependent brash ice resistance formula by modifying the formulas of *Englund* and *Wilhelmson*, which has been implemented in the DSM, see Equation 3.

Equation 3: Channel ice resistance

$$R_{CH} = \frac{1}{2} * u_B * p_\Delta * g * H_F{}^2 * K_p * \left(\frac{1}{2} + \frac{H_M}{2H_F}\right)^2 * (B + 2 * H_F * \left(cos\delta - \left(\frac{1}{tan\psi}\right)\right) * (u_H * cos\phi + \sin\psi * sin\alpha)$$

$$+u_B * p_\Delta * g * K_0 * u_H * L_{PAR} * H_F{}^2 + p_\Delta * g * \left(\frac{L * T}{B}\right)^3 * H_M * A_{WF} * Fn^2$$

Where u_B is 1-p (u_B= 0.8...0.9), p_Δ the difference between the densities of water and ice, g the gravity constant, K_p the coefficient of passive stress, H_M the thickness of the brash ice in the middle of the channel, δ the slope angle of the side wall of the brash ice, u_H the coefficient of friction between hull and ice, ϕ the stem angle of the vessel, α the angle between the waterline and the vertical at B/2, K_0 the coefficient of lateral stress at rest, L_{PAR} the length of the parallel midbody at waterline, A_{WF} the waterline area of the foreship and Fn is the Froude number (Riska et al., 1997). For details, see Appendix F.

The flare angle ψ can be eliminated from Equation 3, by substituting with Equation 4 and 5:

Equation 4: Flare angle

$$\sin\psi = \frac{\tan\emptyset}{\sqrt{sin^2\alpha + tan^2\emptyset}}$$

Equation 5: Flare angle 2

$$\psi = \arctan\left(\frac{tan\emptyset}{sin\alpha}\right)$$

H_F represents the thickness of the brash ice layer which is displaced by the bow that moves to the side against the parallel midbody. H_F is therefore a function of the ship beam, channel thickness and two slope angles, which are dependent on the inner properties of the brash ice, and can be calculated by Equation 6 (Riska et al., 1997):

Equation 6: Displaced brash ice by bow

$$H_F = H_M + \frac{B}{2} * \tan\gamma + (\tan\gamma + \tan\delta) * \sqrt{\frac{B * (H_M + \frac{B}{4} * \tan\gamma)}{\tan\gamma + \tan\delta}}$$

Where the angles γ and δ are calculated, as according to Appendix F, B is the breath of the vessel and the rest is equal to Equation 3. If the breadth of the vessel more than 10 meter and average thickness H_M is over 0.4 meter, H_F, can be approximated by Formula 7:

Equation 7: Simplification of displaced brash ice by bow

$$H_F = 0.26\,meter + (B * H_M)^{0.5}$$

An illustration of the different parameters affecting H_F can be seen in Appendix F

The performance in brash ice can be calculated for a vessel by creating an ice thickness – speed (h-v) curve as described earlier. By combining the net thrust and the resistance curves at different ice thicknesses the h-v curve can be established, which show the speed the vessel can reach at the specified ice thickness. First, the brash ice resistance is calculated for different ice thicknesses, then the net thrust curve is calculated, which is the propeller thrust available to overcome the resistance.

The net thrust can be calculated by the following equation (Riska, 2011a):

Equation 8: Net thrust (Tnet)

$$T_{NET} = K * (P_D * D_P)^{\frac{2}{3}} * \left(1 - \frac{1}{3}\frac{v}{v_{ow}} - \frac{2}{3}\left(\frac{v}{v_{ow}}\right)^2\right)$$

Where K is an empirical factor for bollard pull, P_D is the delivered power, D_P is the diameter of the propeller, v the speed and v_{ow} the open water speed of the vessel. According to Riska (2011a), K is affected by the pitch to diameter ratio of the propeller, and a typical value for K is in the range from 0.8 to 0.85 for a tug with CP propeller without a nozzle, and 0.78 for single screw CPP. Where the resistance curves equals the net thrust curve give the points for the h-v curve. Figure 11 display resistance curves with net thrust and the resulting h-v curve.

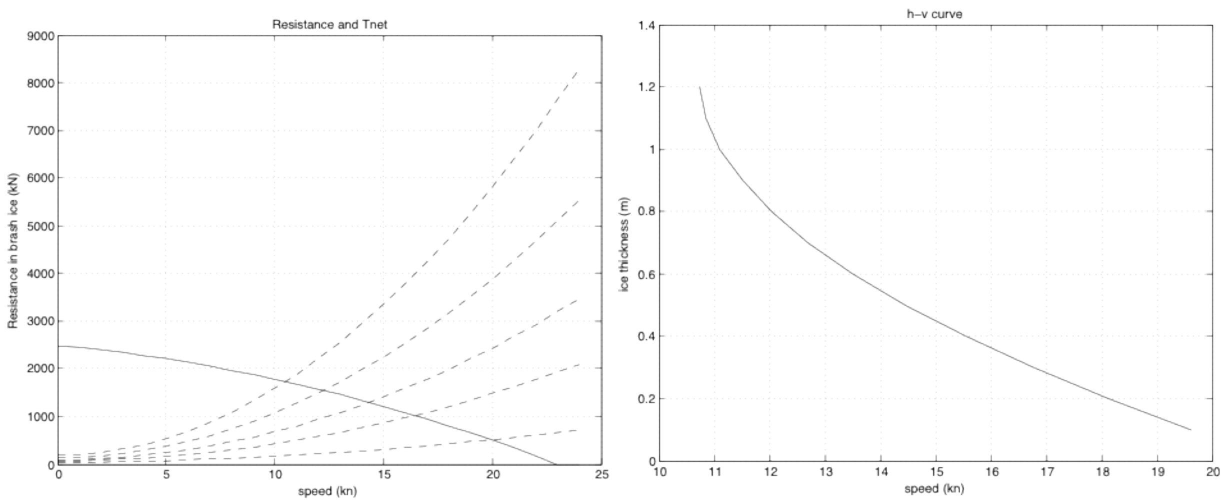


Figure 11: Resistance, Tnet and h-v curve

4.3 Propulsion Efficiency

Propulsion systems interact with the hull, thus the field of flow is changed. These interactions and the open water efficiency of the propeller determine the propulsive efficiency. The propulsion efficiency can according to Schneekluth and V (2007) be calculated by Equation 9:

Equation 9: Propulsion efficiency

$$\eta_D = \eta_H * \eta_R = \frac{R_T * V_S}{P_D}$$

Where η_H is the hull efficiency, η_R the relative rotative efficiency, R_T the resistance, V_S the ship speed and P_D the delivered power at propeller. A typical value for cargo vessels is according to Schneekluth and V (2007) in the range from 0.6 to 0.7 in open water. But for a vessel navigating in ice propulsion efficiency is lower due to ice interaction.

4.4 Open Water Resistance

Power requirements must in early design be estimated to judge the weight and volume requirements. Normally, this is done in design loops (see design spiral, (Lamb, 2004)) , which is time consuming, and the resistance is therefore often estimated based on a few global design parameters. Some of these approaches are:

- Systematically series, such as Taylor Gertler and Series 6, etc
- Regression analysis of different ships, such as Holtrop-Mennen and Hollenbach, etc
- Estimate from parent ship such as by admiralty

Schneekluth and V (2007) describes the abovementioned methods and others in detail. In general, an estimate from a parent ship may give a good estimate if the geometrical properties and speed parameters are close to the design ship (Bertram, 2012). Moreover, the systematic series are according to Bertram (2012) all out-dated, as are most of the regression analysis approaches. Therefore, proper open water resistance estimation should be done using computational fluid dynamics (CFD).

5 Developing a Decision Support Model for Merchant Ships Operating on the Arctic Sea

Having presented methods of implementing the performance in ice and open water in chapter xx, this chapter will present the DSM. Written and operated in MATLAB, the used must first establish the variables by running the script as presented in Appendix K. Furthermore, calculating the results is done by running the script presented in Appendix L, which also presents the results in a .txt and a excel file. The script in Appendix L could be valuable to view at while reading this chapter.

The model is as described in chapter 2, built around the scenario of using the NSR as an alternative to the SCR when the conditions allow it, although it could also be used for other transport scenarios where open water routes competes with ice infested routes. For a ship owner investigating design alternatives the model will be a valuable tool for evaluating new ship projects.

The model has been developed for container vessels of ordinary hull form with size from 1500 to 11000 TEU payload capacity, though it could be modified to fit any kind of vessel. The following section deals with two route alternatives; here the route that includes navigating in ice, and the open water will be nominated ice route and open water route, respectively.

Based on the inserted distances for the route alternatives and the time to navigate them, the speeds are calculated; First, the navigating time is established by subtracting the port time from the total time of the trip, and the speeds are calculated by dividing the distances on the navigating time given by the schedule.

The ice route, which can consist of ice, is split into two, one for ice and one for open water. The model uses simplified ice conditions where two parameters are used to represent the ice, which are thickness and extent. Furthermore, depending on the extent and thickness of ice and the vessels performance in the corresponding conditions, the speed and time used in the open water part of the ice route is calculated. Consequently, if the ice extent is large, the vessel speed of the open water part must be higher as the speed in ice generally is low. Equation 10 describes the relationship of the different parts of the ice route.

Equation 10: Relationship of distances on ice route

$$d_{owice} = d_{totice} - d_{ice}$$

Where d_{owice} is the open water part of the ice route, d_{totice} the total distance of the ice route, and d_{ice} the distance of the ice extent. By altering the extent of ice (d_{ice}), the user can find under what conditions operating on the NSR can be beneficial or not. Other then presence of ice, the model does not take into account other delays that could occur such as; heavy wind, compressing ice conditions, fog, and waves etc.

The operational time in ice represents the difference in ice class performance. Annual trips using ice route is calculated on the basis of the operational time in ice, and the remaining annual operating time is therefore used for the open water route, see Equation 11. Hence, the number of annual trips for the transport system is the sum of trips using ice route and open water route.

Equation 11: Calculating trips on open water

$$trip_{ow} = \frac{(t_{operating} - t_{ice})}{t_{sea}}$$

Where $trip_{ow}$ is the number of trips in open water, $t_{operating}$ the total annual operating time, t_{ice} the allowed time navigating the ice route as a result of ice class and t_{sea} available time to navigate as calculated given on trip time and port time. If the vessel is only supposed to navigate the ice route, such as the NSR, the operational time t_{ice}, on the NSR should be equal to the total operational time ($t_{operating}$), and zero if only operating the open water route (SCR).

Using the service schedule and the payload capacity of the vessel, the annual cargo transported is calculated. The model incorporates an average capacity utilization, which is assumed equal for both ways, and if one wants to account for uneven capacity utilization depending on which way one navigates, one should use the average of both.

5.1 Speed in Ice and Open Water

As earlier mentioned the model takes into account the ice extent and the thickness of ice, based on these parameters the speed in ice and corresponding time used in ice is calculated. The model is made under the assumption that merchant vessels navigating in ice will use the channels created by the icebreakers. As a result, the resistance applicable to the merchant vessel is the brash ice resistance of navigating in the broken channel of ice.

The speed navigating in ice is calculated as a function of net trust and brash ice resistance in different brash ice thicknesses, as described in section 4. Speed, resistance and fuel consumption in ice and open water are directly linked, and important factors to be included. Based on the open water speed, the power delivered by the propellers and resistance curves in brash ice for different ice thicknesses the model will calculate the speed in ice as a function of ice thickness.

In order to make the model valid for different sizes of container vessels fuel consumption data for different sizes of container vessels have been used to establish equations for propulsion power, see Notteboom and Vernimmen (2009). Based on these data, and assuming a specific fuel consumption (SFC) of 190 [g/kWh], regression has been used to develop propulsion power and resistance equations for different sizes of container vessels, see Figure 12 and Appendix J.

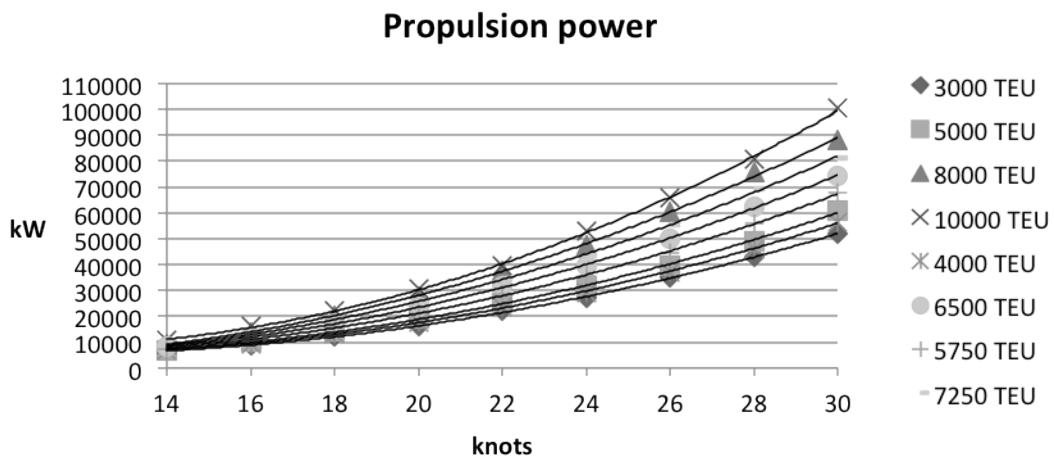


Figure 12: Propulsion power

Based on the calculated propulsion power, the corresponding open water resistance can be calculated according to Equation 12.

Equation 12: Resistance open water

$$R_{ow} = \frac{P_{power} * (1 - P_{loss})}{V_{ow}}$$

Where R_{ow} is the open water resistance, P_{power} is the power delivered from the engines at corresponding speed, P_{loss} accounts for losses such as mechanical. etc. and V_{ow} is the speed in open water.

5.2 Costs

The ice conditions on the Arctic Sea are the most important factor for the economy of shipping through the route. The ice conditions will dictate the time used on each trip, the number of trips annually, the cost of navigating and the maintenance costs of the ship, amongst others. The ice conditions used in the model should represent the average ice conditions in the timeframe the vessel operates on the ice route. Thus, if the time allowed in ice were to be equal to for example one year, the extent of ice and thickness should be the average of the same period.

Fuel costs are calculated as the sum of consumption from the time spent in ice and open water using the propulsion power and resistance in ice as described earlier. For ice the fuel consumption is calculated according to Equation 13.

Equation 13: Fuel consumption ice

$$Consumption_{ice} = sfc * t_{icewater} * p_{power}$$

Where $Consumption_{ice}$ is the fuel consumption in ice, sfc the specific fuel consumption of the engines, $t_{icewater}$ the time used in ice and p_{power} is the propulsion power. The propulsion power used here is at 80 % mean continuous rating (MCR) as used in the net thrust calculations for the speed in ice. As $t_{icewater}$ is determined from the ice condition and speed in the corresponding condition. Thus, consumption in ice is directly linked with the ice conditions and the parameters of the vessels investigated. Consumption for open water is calculated in a similar matter, and the two make up the annual bunker consumption. Consumption of MDO used in harbours etc. has been left out of the model.

When a ship navigates in ice, ice is being pushed sideways and under the vessel, as a result, damage on the ships hull, appendages and propeller(s) is increased. Therefore the maintenance costs are assumed doubled for the fraction navigated in ice compared to maintenance costs of open water. An additional annual insurance premium for navigating in ice is also incorporated; it is assumed that one must pay this to be allowed to navigate in ice, which is a function of number of trips. The additional expenses except fuel of navigating in ice is given in Equation 14.

Equation 14: Expenses from ice navigation

$$C_{expencesice} = c_{insuranceice} * trips_{iceroute} + \left(\frac{c_{maintenance} * 2}{d_{totalannual}}\right) * d_{iceannual}$$

Where $C_{expencesice}$ is the expenses resulting from navigating in ice, $c_{insuranceice}$ is the insurance premium, $c_{maintenance}$ the maintenance cost of open water, $d_{totalannual}$ the total annual distance travelled and $d_{iceannual}$ is the annual distance sailed in ice. The maintenance and insurances expenses occurred from navigating in open water is calculated in a similar matter, although the maintenance cost is not doubled.

In order to give a realistic cost of running the vessel, emphasis has been put on leaving out only minor costs. As a result, the model incorporates many different costs, such as cost of cargo handling, cost of onshore and crew personnel, cost of sales, channel fees including icebreaking fee and capital costs etc.

For a typical ship, the capital costs can account for as much as 39 % of total costs (Stopford, 2003). The model incorporates the capital costs for the first year of the ships lifetime. Using the input such as equity of ship price, cost of ship, interest rate, loan time and lifetime of ship and a assumed 20 % residual scrap value, the annual capital costs in terms of interest, back payments and depreciation is calculated according to Equation 15.

Equation 15: Capital costs

$$C_{repayments} = \frac{gearing}{100} * C_{ship} * \frac{i * (1+i)^n}{(i+i)^n - 1}$$

Where $C_{repayments}$ is the annual repayments including interest, $gearing$ the percentage of equity of ship cost C_{ship}, i the interest rate and n the loan time in years.

5.3 The Required Freight Rate and Life Cycle Cost

By summing all the running costs of the vessel including the capital costs as described above, and calculating the net present value of them over the lifetime of the vessel, the total life cycle cost (LCC) is calculated as shown in Equation 16.

Equation 16: Life cycle costs

$$LCC = c_{annual} * \frac{(1+i)^n - 1}{i * (1+i)^n}$$

Where c_{annual} is the all-annual costs of running the vessel and the rest of the equation is equal to Equation 15. Using the same values, the needed income to cover the costs are calculated, and divided by the annual cargo carried, giving the RFR. The LCC and the RFR are valuable tools for project economy and can also be used in direct comparison of ship designs. The RFR basically shows what the minimum freight rate must be to cover all the costs for the ship owner. The lower the RFR the better for both the ship owner and costumers paying for the service provided. The RFR is calculated based on the LCC occurred from sailing the specific schedule over the lifetime of the vessel. The SMF also accounts for costs, as will be shown in the following section, but the strength is that it combines several technical aspects in addition.

5.4 The Ship Merit Factor

The SMF presented here is a modified combination of the ones described in (Polach et al., 2012) who introduced the SMF for ice and (Harries, Abt, Heinemann, & Hochkirch, 2006). According to Harries et al. (2006) and Polach et al. (2012), the SMF is a techno-economic approach to compare ship variants in the field of hydrodynamic ship design. The units of the ship merit factor are [TEU*miles/year *USD] and a higher SMF therefore represents a larger return on investment, see Equation 17.

Equation 17: Ship Merit Factor

$$SMF = k * \frac{P_D}{AAC} * \frac{W_{PL}}{R_T} * \eta_P$$

Where P_D is the power delivered, W_{PL} the payload of the vessel, R_T the total resistance, η_P the propulsion efficiency, and AAC compromise the annual operating cost of the vessel including capital costs. The service factor k is described in Equation 18 below.

Equation 18: Service factor for SMF

$$k = 8760 \frac{hours}{year} * f_S * f_L * f_V * f_P$$

Where f_S is the utilization factor, f_L the load factor, f_V the operating speed factor and f_P the port time factor. For details please look at Appendix L under SMF calculations. The service factor k is calculated for both SMF_{ow} and SMF_{ice}, and therefore each ship merit factor represents the performance of the design on the specific route.

As this model is built for a vessel with the possibility of using two routes, it has one SMF for each route. One for the open water route, and one for the ice route, hereby nominated as SMF_{ow} and SMF_{ice}.

With SMF_{ow} being the one for open water route, the resistance R_T represents the open water resistance, and the η_P represent the propulsion efficiency for open water. The costs AAC are assumed equal for both ship merit factors, as it is considered to be the same ship. However, the costs as calculated in such a manner that no costs from navigating the ice route will be accounted for if it does no do so, and vice versa.

As the model uses two ship merit factors, it also uses two service factors. Therefore one service factor is calculated for each route, which then is dependent on the number of trips achieved on each route and the average speed of the route, amongst other factors. For the service factor (k) for ice, which contains two different speeds, the weighted average is calculated. The resistance R_T and the η_P for the ice route are also calculated by the equivalent weighted average, as shown below for R_T in Equation 19.

Equation 19: Average resistance on Ice Route

$$R_{ice} = \frac{R_{ch} * d_{ice} + R_{ow} * d_{owice}}{d_{ice} + d_{owice}}$$

Where R_{ice} is the average resistance for the ice route, R_{ch} the channel ice resistance (brash ice), R_{ow} resistance in open water, d_{owice} the distance of open water on the ice route, and d_{ice} the distance of ice extent.

By studying the SMF and the service factor k, one can see how the SMF and the design evaluated can be improved by:

- Increasing speed,
- Reducing port time,
- Increasing utilization,
- Increasing cargo utilization,
- Reducing cost,
- Increasing cargo capacity,
- Reducing resistance and/or
- Increasing propulsion efficiency.

For vessels that combine the ice and open water route, the sum of the two ship merit factors is used, as shown in Equation 20 below.

Equation 20: Total Ship Merit Factor

$$SMF_t = SMF_{ow} + SMF_{ice}$$

Therefore, by altering and playing with the different input parameters of the model, the decision maker can find the suitable scenario and what other prerequisites that must be in place in order to invest in an ice classed vessel for the NSR and make it profitable. In addition, the SMF_t can be used in the similarly in order to optimize the design, also with respect to ice class, while the LCC and the RFR can be used to measure the economic performance.

5.5 Evaluation

To validate the model, sensitivity for different parameters have been conducted, that way the behaviour of the model can be assessed. The emphasis on the evaluation will be on the SMF_{ice} as it takes ice conditions and performance in ice into consideration in addition to what mentioned earlier.

The design used in this evaluation and its parameters is presented in Appendix A. The design is a container vessel designed for open water with a design speed of 24 knots.

5.5.1 Altering Speed

In the model the speeds are calculated on basis of the fixed schedule as described in section 5. Therefore, this sensitivity is only to show how the model behaves when speed is altered.

5.5.1.1 Altering speed 1: No ice

Here the SMF_{ice} is investigated for altering speed. As there is no ice, the only speed applicable is the speed in open water. Below the sensitivity plots for the RFR and SMF is presented in Figure 13. As speed increases, as will the resistance and thus the fuel cost. The RFR will first drop due to the increased tonnage with increased speed, until the costs become the dominant factor due to the higher resistance. The development is very much the same for the SMF, for the same reasons. At lower speed, where the fuel costs increase less, the service factor will grow due to the increased speed factor. As with the RFR, the fuel costs will raise significantly as speed becomes higher, and therefore the SMF will drop as the operational costs become higher.

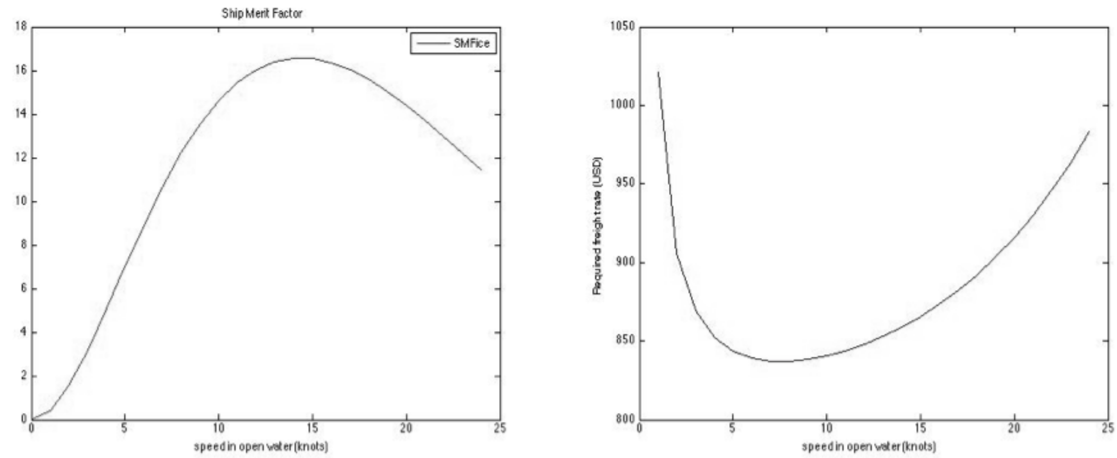


Figure 13: SMF and RFR for altering speed

5.5.1.2 Altering Speed 2: Ice

As will be shown, presence of ice very much influences the economy and the SMF. Here, the extent of ice is set to 1000 nm, and the total distance of the ice route to 7000, and the remaining open water part 6000 nm long. The distance of ice is kept constant and has a thickness of 0.5 meter. As the speed in open water for the ice route is a direct consequence of the ice extent and time spent in ice, the speed in ice (V_{ice}) is altered.

One of the problems of the fixed schedule is that there is depending ice conditions a chance that the vessel cannot navigate the route in the within the given timeframe. As the speed in ice increases, and the distance of ice is kept constant, the speed of the open water part decreases. This also works the other way around, so if the time in ice increases, due to either ice extent or low speed, the speed in the open water part must increase. Hence it must be checked that the speeds calculated are reasonable and within the boundaries of the design.

For the sensitivity case here, as shown if Figure 14 the open water speed gets as high as 30 knots when the speed in ice is 2 knots, which is well above what the ship is designed for. This is also reflected in the sensitivity plots shown below, when the open water speed is that high, the fuel costs are equally high. Therefore the RFR is high and SMF low at the mentioned speeds. As the speed in ice increases, the speed in open water decreases, and the operating speed factor will decrease slightly, resulting in a lower service factor. Combined with higher resistance in ice with corresponding higher costs it is explained why the SMF drops and the RFR increases as the speed in ice increases.

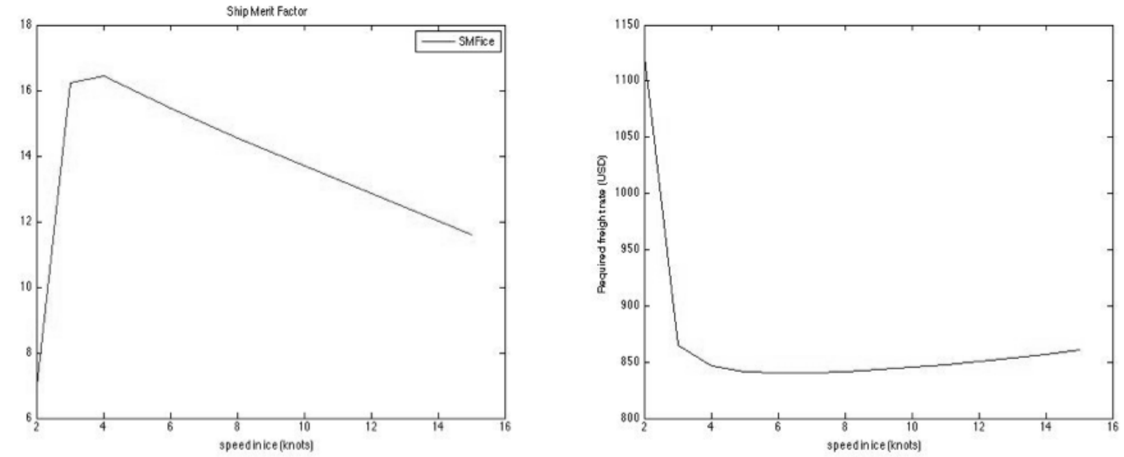


Figure 14: SMF and RFR for speed in ice

5.5.2 Altering Ice Extent

The extent of ice on the ice route is the single most important parameter for the economy of the route, and with increased ice extent, the longer time with higher resistance, lower speed and corresponding higher costs. As a result, the SMF and RFR will both develop negatively with increased ice extent along the ice route. In Figure 15 sensitivity is shown for increasing ice extent with speed in ice constant at 10 knots and 0.5-meter brash ice thickness.

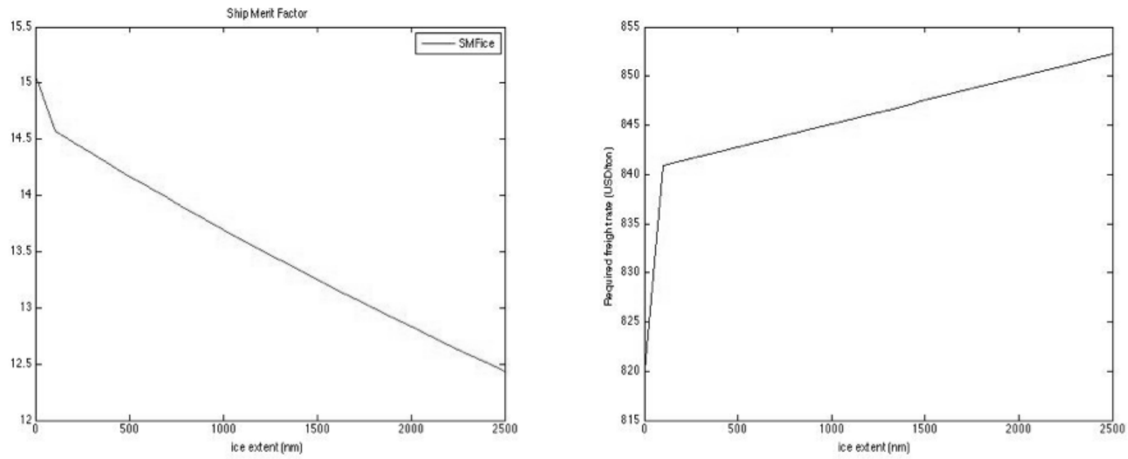


Figure 15: SMF and RFR for altering ice extent

5.5.3 Altering operational time on ice route

As already mentioned briefly, the operational time in ice influences the number of trips the ship can navigate using the ice route. Vessels with higher ice class can benefit from additional trips compared to a design with a lower ice class. However, if the vessel were to only make 3 knots of speed in heavy ice contions for an extended periode of time, the use of the ice route would not be benefitial. Thus, the ice conditions will dictate whether or not increasing operational time in ice will benefitial.

For vessel navigating both routes, the SMF_t can be used to assess how the design will perform. A vessel using both routes, will be a compriomize in desing, but it can make a higher profit from using the ice route. That will however depend on the costs ocurred from ice navigation. In Figure 16, sensitivy for the RFR can be seen for increasing operational time on the ice route and thus an increased numer of trips using it.

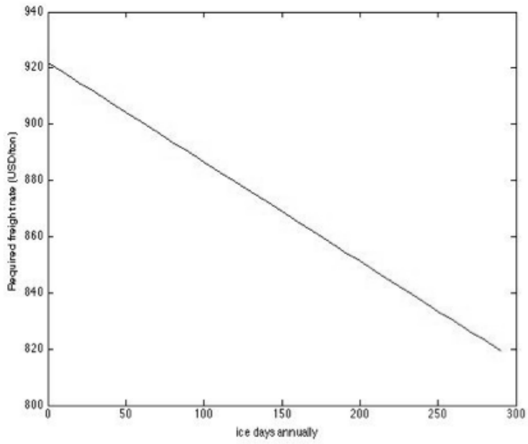


Figure 16: RFR for altering operational time on ice route

As the operational time in ice increases, the number of trips throught the ice route will increase as well, and as there is no ice for this scenario. The fuel costs will fall due to the lower speed and resistance as the distance is shorter as seen in the RFR in Figure 16.

Increasing the operational time in ice only affect the service factor k, which will decrease for the SMF_{ow} and increse for the SMF_{ice} as time on the respective routes changes. More specifically, the porttimefactor will change in opposite directions for both routes. As the ship design is performing worse on the ice route, the SMFtot will decrease as the number of trips on the ice route increases. This is more clearly shown in Figure 17, where parameters are kept equal, except that there is 1500 nm of ice on the ice route

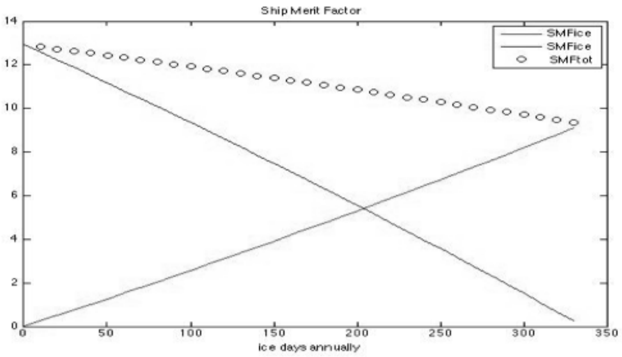


Figure 17: SMF for increasing operational time on ice route with presence of ice

With the DSM presenting reasonable results on the given input, the following chapter will assess a SCR vessel on the NSR under the scenario as described above.

6 Case study

The ship-owner who wants to utilize the NSR as an alternative to the SCR, must calculate the cost versus benefit of investing in a more expensive vessel capable of navigating the NSR. Therefore, chapter presents two case studies, first the model is used to evaluate the performance of an SCR vessel put on the NSR with the fitted requirements. The second case shows briefly how the design of the SCR vessel could be improved which is measured with the SMF.

6.1 Case 1: Measuring performance of a SCR ship on the NSR

For this case it will be measured qualitatively how well an SCR design will perform when fitted with an ice class in addition to fulfilling the other requirements needed to navigate the NSR. Different ice classes of the FSICR have been assessed, which have been differentiated by investment cost and operational time in ice. This case study was conducted to answer the following:

- Design performance
- Economics of navigating NSR
- Evaluating conditions and scenarios for NSR profitability
- Evaluation of ice class

Results for the different ice classes of FSICR have been calculated, which are then compared with an SCR vessel not being able to use the NSR as it is lacking ice class. Today, as described earlier, the requirement is that one must have an ice class equivalent to 1A in order to navigate the NSR. In the summer time ice class 1B can be allowed to use the route, based on special allowance and inspection from the MOHQ and given favourable ice conditions. However, as these requirements can change together with the future ice conditions, all ice classes of the FISCR has been accounted for in the case study.

6.1.1 Vessel Design

A traditional container design for open water has been established in order to perform a case study on it. The main parameters are presented in Table 8 below. For further details see Appendix A.

Table 8: Parameters of design for Case1

Length	250	m
Beam	34	m
Draught	12	m
Displacement	65000	ton
Deadweight	50000	ton
Payload	3800	TEU
Gross tonnage	40000	ton

The main parameters have been established using data provided by Levander (2009) in his book System Based Ship Design. Using the hull drawings as shown in Appendix A, the input angles for the brash ice resistance have been established.

Table 9:Parameters for ice resistance

Length parallel (Lpar)	130	m
Awf	806.5	m^2
α	23	°
Φ	90	°
Propeller diameter (CPP type) (Dp)	7.5	m
Delivered Power (Pd)	24.5	MW

The water plane area of the bow (Awf) has been calculated by integrating the coordinates of the bow sections, as shown in Appendix A. The other parameters used for the brash ice resistance, K_p and Ko, which are uncertain, has been assumed to 6.5 and 0.68 respectively, p_Δ as 150 and u_H assumed to 0.02. The channel ice angles γ and δ has been taken to 2 and 22.6° as according to (Riska et al., 1997). The bollard pull coefficient for the net thrust calculations has been taken to 0.78 and u_B has been taken as 0.8, as according to (Juva & Riska, 2002). See Appendix F.

Table 10: Propulsion details

Propulsion power	35	MW
Prop. Efficiency ice	0.6	-
Prop. Efficiency open water	0.7	-
Specific fuel consumption	190	g/kWh

The propeller efficiency has been taken to 0.7 as a good estimate according to Schneekluth and V (2007). For ice the propeller efficiency is lower due to ice interaction, and has been assumed to 0.6 as shown in Table 10. The propeller diameter (Dp) has been guesstimated using the lines plan in Appendix A, and allowing for some clearance, see Table 9. For the delivered power (Pd) the propulsion power has been used while taking into account some losses (mechanical etc.) that have been assumed to 30 %. The propulsion power estimate of 35 MW and delivered power (Pd) is more than enough to qualify for ice class 1AS of FSICR according to the calculations in Appendix C.

To control the validity of the propulsion power and resistance data used in the model with the resistance of the vessel design in this case study; the resistance curve of the vessel has been calculated according to the method of Guldhammar/Harvald, see (Schneekluth & V, 2007).

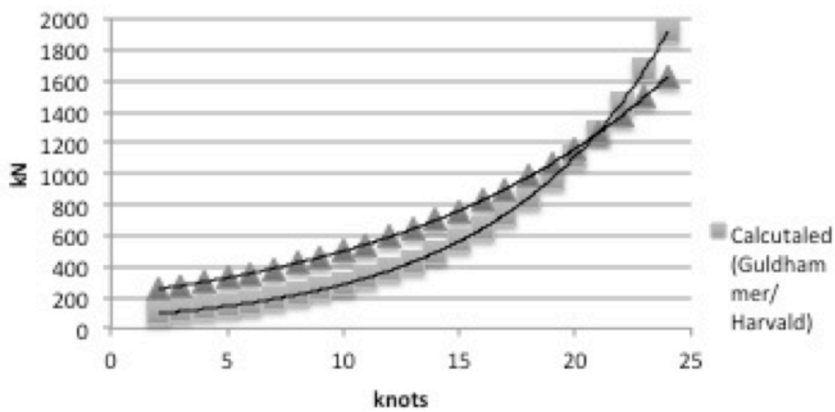


Figure 18: Comparing resistance of case vessel and model resistance

As can bee seen from the resistance curves in Figure 18, the calculated and the data used in the model deviate quite a bit. For the vessel under investigation the model will give too high consumption especially when slow steaming, and too low when pushing speeds above 22 knots. Still, the consumption data will be equal for all design alternatives with respect to ice class in this case study and are therefore assumed to bee valid as they all have the same hull shape. However, it shows that for cases where the hull shape is different between design alternatives, the resistance and propulsion power equations should be implemented for each alternative. Details concerning the resistance calculations are presented in appendix D.

6.1.2 Establishing Costs

In order to calculate the SMF and the RFR a set of costs have been established as displayed in Table 11. The general costs are kept equal for all ships in order to compare them.

Table 11: Costs for case study

Cost		Unit	Source
Average annual cost pr. crewmember	30000	USD	Levander, 2009
Insurance SCR	40000	USD	Erikstad/Ehlers 2012-
Insurance NSR	40000	USD	Erikstad/Ehlers 2012-
Annual maintenance	1	% of ship value	-
Cost of HFO	700	USD/ton	Bunkerworld.com
Cost of cargo handling	150	USD/TEU	Levander, 2009
Cost of sales	100	USD/TEU	Levander, 2009
Cost of port call	0.5	USD/GT pr. port call	Levander, 2009
Channel fee Suez	Calculated	-	-
Channel fee NSR	5	USD/ton	-
Number of crew	20	Positions	-
Number of seagoing positions pr. crew position	2.2		Levander, 2009
Overhead shore crew	250	%	-
Number of shore personnel	20	Positions	-
Interest for loan and NPV	8	%	-
Lifetime ship	25	Years	-
Repayment time of ship loan	18	Years	-
Equity on ship loan	40	%	-
Scrap value of vessel	20	% of ship price	-

The various costs are gathered from different sources, although many are from Levander (2009), and emphasis have been put on keeping them reasonable. The crewing costs are kept equal for all vessels, although it most likely will be more expensive to crew the vessel navigating the NSR, this cost is insignificant in the big picture. Crewing the NSR vessel is likely more expensive due to additional crew requirements such as ice navigation training, cold climate and so forth.

The cost of cargo handling and sales, which are quite significant, are a function of cargo carried, and as the designs compared travel the same schedule these annual costs are equal. The cost of insurance is set to 40 000 USD per trip for both routes as according to Erikstad and Ehlers (2012). The channel fee for the Suez channel is incorporated in the model with the formula as provided by (www.suezcanal.gov.eg), and the fee for NSR is set to 5 USD/ton as according to Erikstad and Ehlers (2012). The cargo weight of one TEU is set to 12 ton as according to Stopford (2003).

The cost of the vessel and the time allowed to navigate in ice is the only parameter different for the ice classes investigated. The values for additional ice class cost and ice days as shown in Table 12 are gathered from (Erikstad & Ehlers, 2012), who refers to Polach et al. (2012) regarding the costs. The cost of a no ice class vessel has been guesstimated to 60 M. USD.

Table 12: Ice class differences

	No ice class	1C	1B	1A	1AS	Unit
Ship cost	60	63.9	64.5	65.7	67.2	M USD
Additional cost	0	7	8	10	12	%
Time in ice	0	86	91	99	105	Days
Ice thickness	0	0.4	0.6	0.8	1	m

According to the work of Erikstad and Ehlers (2012), the number of operational days along the NSR will increase each year, but the differences between the respective ice classes will remain constant, see Figure 6. For the capital costs, the interest has been set to 8 %, the equity ratio on the ship price has be set to 40%, and the down payment time of the vessel to 18 years.

6.1.3 Ice Conditions

The extent of ice can be measured quite easily by satellite images, but the thickness is harder to measure. Due to the uncertainty of the ice conditions along the NSR calculations has been performed for several ice scenarios by altering the average ice extent and thickness as shown in Table 13. It has been assumed that the thickness of ice will increase with the extent.

Table 13: Ice scenarios

Ice extent as percentage of NSR	Average thickness (m)
0	0
25	0.4
50	0.8

The distance of the NSR is taken to be 2500 nm, thus if 25 % is covered with ice, it will correspond to a distance of 625 nm etc.

6.1.4 Schedule and Route

The vessels use a fixed schedule with 14 annual trips, which take 25 days including 42 hours in port as provided by (Omre, 2012). Here, the route between Rotterdam and Yokohama with the distances as described in Table 2 has been used, while the distance of the NSR has been taken as 2500 nm.

The vessels will therefore slow steam the NSR due to the shorter distance, however the slow steaming speed in open water on the NSR will depend on the ice conditions. If there is much ice, hence using much time in ice where the speed is lower, the speed on the open water part must be higher to keep the schedule. The operational time in ice for the different ice classes as suggested by Erikstad and Ehlers (2012) as shown in Table 12, shows that the difference is not that large. For the current schedule of 25 days for each trip, only an increase from ice class ice class 1C to 1A will give approximately one more trip using the NSR. The capability of the ice classes with regards to ice thickness does on the other hand differ more. In order to have a feasible schedule, the operational time in ice has been altered so that vessels with ice class 1C and 1B will be able to make 3 trips on the NSR, while vessels with ice class 1A and 1AS will be able to make 4 trips as shown in Table 14.

Table 14: NSR trips as result of ice class

	No ice class	1C	1B	1A	1AS
Trips NSR	0	3	3	4	4

6.1.5 Speed in Ice

As the speed in ice as described above is calculated from the parameters of the vessel, it is assumed that the icebreaker is capable of breaking ice in the same speed in the given ice conditions, if they were to be escorted. This could be rough assumption, however, according to the fleet information available at (www.rosatomflot.ru) the icebreakers are in typically capable of breaking up to 2-meter thick level ice. If one assumes a linear relationship between speed and ice thickness, the icebreakers are capable of breaking 1-meter thick ice at 10 knots, see Figure 19. This is in addition a quite conservative estimate, as the speed at 2 meter is set to zero, if it is capable of breaking level ice at a steady pace, the speed should be around 2-3 knots at 2-meter ice thickness.

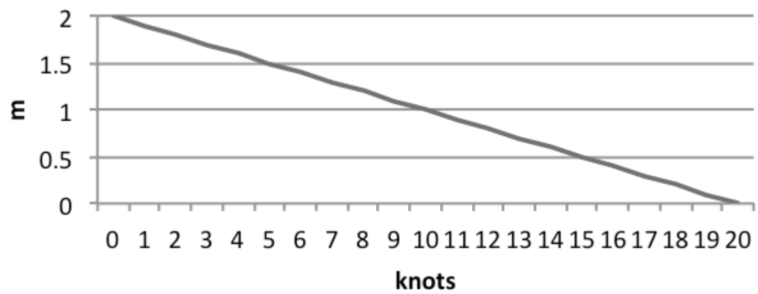


Figure 19: Rough H-V curve for nuclear icebreakers

It should be noted that the ice thicknesses referred to here is the average thickness of the brash ice. Normally the thickness of the level ice will be thicker as ice is being pushed sideways by the icebreaker leaving a thinner cover of brash ice.

6.2 Results Case 1

6.2.1 Performance in Ice

Using the parameters of the design, the performance in ice has been calculated by the DSM, creating an h-v curve as seen in Figure 20, together with the resistance and net thrust calculations.

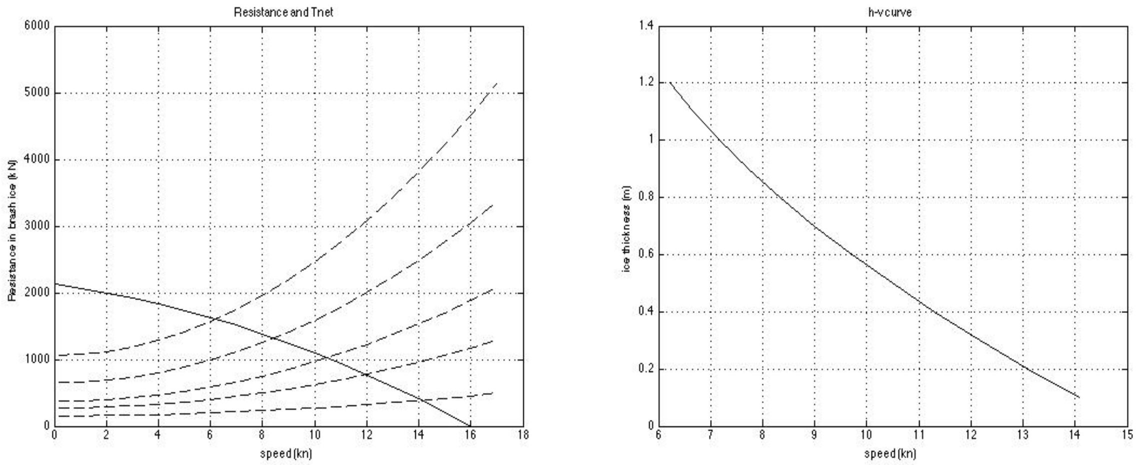


Figure 20: Calculated reistance, Tnet and h-v curve for Case1 vessel

Due to the high open water speed of the vessel at 24 knots and hence large installed power, the vessel is capable of navigating in high speeds in brash ice as well.

6.2.2 No I*ce*

As the first scenario, the performance and economy of navigating the NSR if there is no ice along the route has been calculated. The results can bee seen in Table 15, where the vessel with ice class 1A turns out to be the best alternative with regards to all measured results. The results are presented with more details in Appendix H. Clearly, it is cheaper to navigate the NSR if there is no ice along the route than using the SCR. Therefore, as can be seen in Table 15, ice class 1A and 1AS which can make 4 trips performs better than ice class 1C and 1B which will manage 3 trips. As ice class 1A can make 4 trips with the lowest costs due to the lower vessel price compared to 1AS for the same amount of trips using NSR, ice class 1A turns out to be the best alternative.

Table 15: Results no ice

		NO ICE				
		SUEZ	**1C**	**1B**	**1A**	**1AS**
LCC	USD	$489,490,000.00	$466,000,000	$471,000,000	$465,000,000	$466,000,000
RFR	USD/TEU	1149.30	1095.30	1106.10	1091.00	1094.60
SMF_{ow}	(TEU*mile)/USD	8.76	7.22	7.15	6.59	6.57
SMF_{ice}	(TEU*mile)/USD	0.00	2.09	2.07	2.80	2.79
SMF_{t}	(TEU*mile)/USD	8.76	9.32	9.22	9.39	9.36

With 4 trips on the NSR with no ice the fuel annual fuel costs are reduced with 7.3 %, while the average required freight rate is reduced with 55 (USD/TEU) for ice class 1A compared with the Suez vessel. For a single trip through NSR the fuel costs are reduced with 60 % compared with Suez, due to the reduced speed of 13 knots compared to 20 knots at SCR.

6.2.3 25 % of NSR covered with 0.4 m ice

With 625 nm of the NSR covered ice the costs of navigating in ice and the higher resistance begins to affect the results. Thus the performance of the ice-classed vessel becomes lower. As one can see from Table 16, ice class 1A is still the preferable alternative, with the highest SMF_t and lowest LCC and average require freight rate. Hm represents the average brash ice thickness in the ice channel.

Table 16: Results 25% ice extent, 0.4m brash ice thickness

Ice extent= 25 %, hm= 0.4 m						
		SUEZ	1C	1B	1A	1AS
LCC		$489,490,000	$475,000,000	$476,000,000	$471,000,000	$473,000,000
RFR	USD/TEU	1149.30	1116.30	1117.80	1106.60	1110.30
SMF_{ow}	(TEU*mile)/USD	8.76	7.09	7.08	6.50	6.48
SMF_{ice}	(TEU*mile)/USD	0.00	1.91	1.91	2.57	2.56
SMF_t	(TEU*mile)/USD	8.76	8.99	8.98	9.06	9.03

The presence of ice results in higher fuel consumption and maintenance costs. However, compared to the SCR, the vessel is still consuming approximately 50 % less fuel per trip on the NSR, with C02 emissions correspondingly reduced.

6.2.4 50 % of NSR covered with 0.8 meter ice

With brash ice thickness of 0.8 meter covering 50 % of the NSR the effect and costs occurred from navigating in ice are becoming high. By comparing the RFR and the LCC ice class 1A is marginally better. The SMF_t does on the other hand show that the ice class vessels perform worse than the Suez vessel with respect to design as shown in Table 17.

Table 17: Results 50% ice extent, 0.8m brash ice thickness

Ice extent= 50 %, hm= 0.8 m				
		SUEZ	1A	1AS
LCC		$489,490,000.	$486,000,000	$488,000,000
RFR	USD/TEU	1149.30	1141.40	1145.10
SMF_{ow}	(TEU*mile)/USD	8.76	6.30	6.28
SMF_{ice}	(TEU*mile)/USD	0.00	2.13	2.12
SMF_t	(TEU*mile)/USD	8.76	8.43	8.40

The reason for the SMF_t being lower is due to several factors. As the propulsion efficiency is less in ice, the total propulsion efficiency, together with the operating speed factor, becomes lower as the distance in ice increases. Although the most important factor is the increased resistance, which becomes more governing as distance in ice increases.

6.2.5 Sensitivity

6.2.5.1 Operational Days Along NSR

The operational days in ice decides the number of trips using the NSR. However, the ice conditions will be the deciding factor to whether it is beneficial or not. As can be seen in Figure 21 below, which shows the SMF_t and the RFR, increasing the operational time in ice and thus the number of trips using the NSR is advantageous with the ice conditions as described.

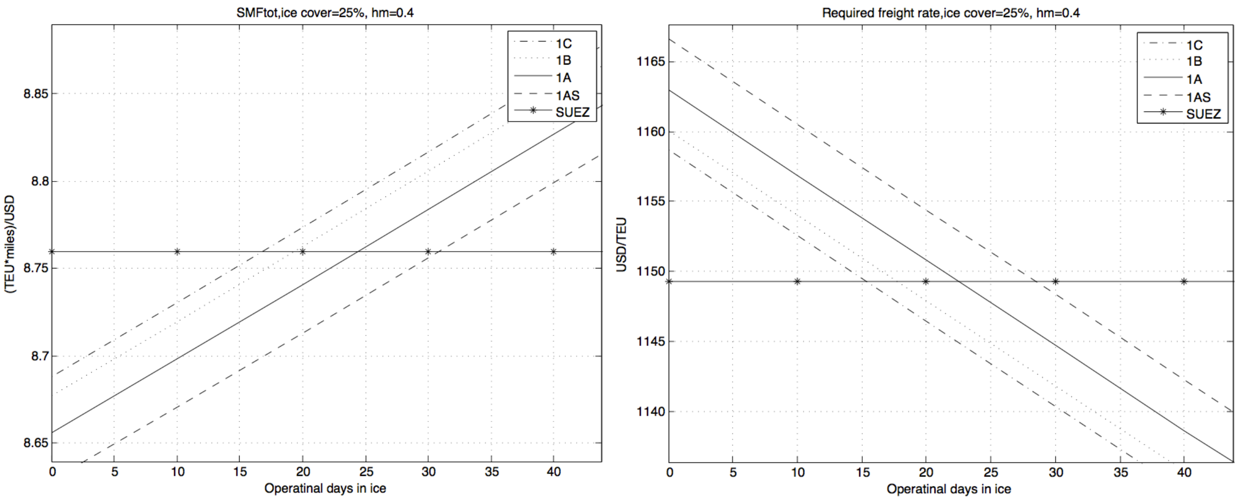


Figure 21: Sensitivity for operational days on NSR (1)

The RFR shows in Figure 21 shows that ice class 1C will need fewer trips on the NSR then 1AS under the given ice conditions, due to the additional investment cost of ice class 1AS. However, at the current schedule, the additional days needed is less than one trip through the NSR.

When there is more and thicker ice, as shown for SMF_t and RFR in Figure 22 below, the ice classes 1A and 1AS, which are the ones still allowed to navigate in the 0.8 meter this brash ice, need several days than compared to the ice conditions in Figure 21 above. Although the design performance is lower then the SCR vessel, the ice-classed vessels are able to make profit if the operational time on the NSR is above approximately 60 days.

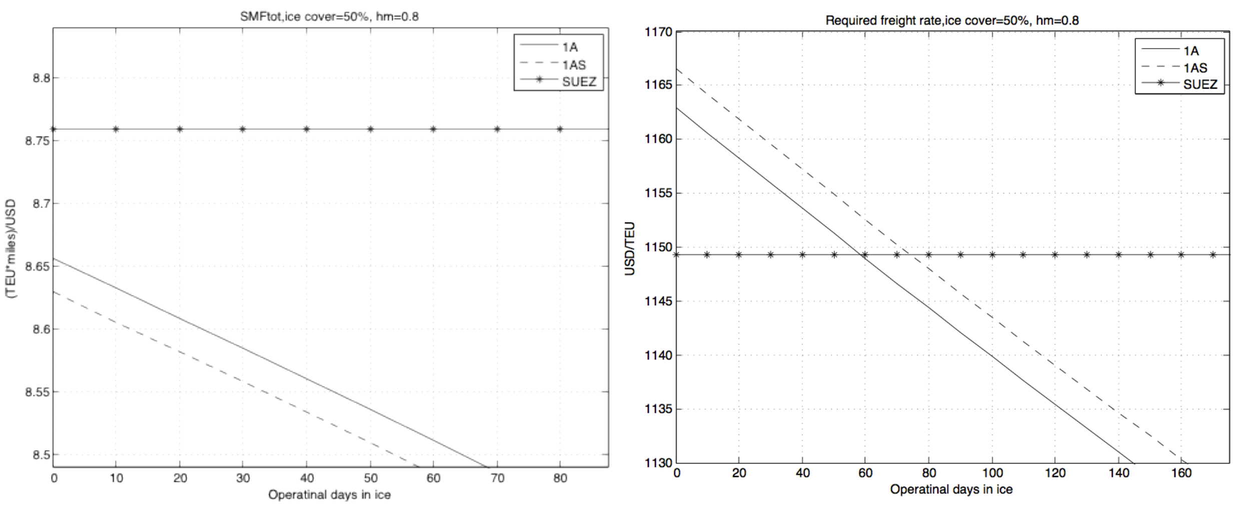


Figure 22: Sensitivity for operational Days on NSR (2)

6.2.5.2 Extent of Ice

The extent of ice with its corresponding thickness is the single most important factor for the potential profitability of using the NSR. By calculating sensitivity plots for the extent of ice, the conditions where using the NSR can be beneficial is shown. In Figure 23, sensitivity for extent of ice is calculated for brash ice thickness 0.4 meter.

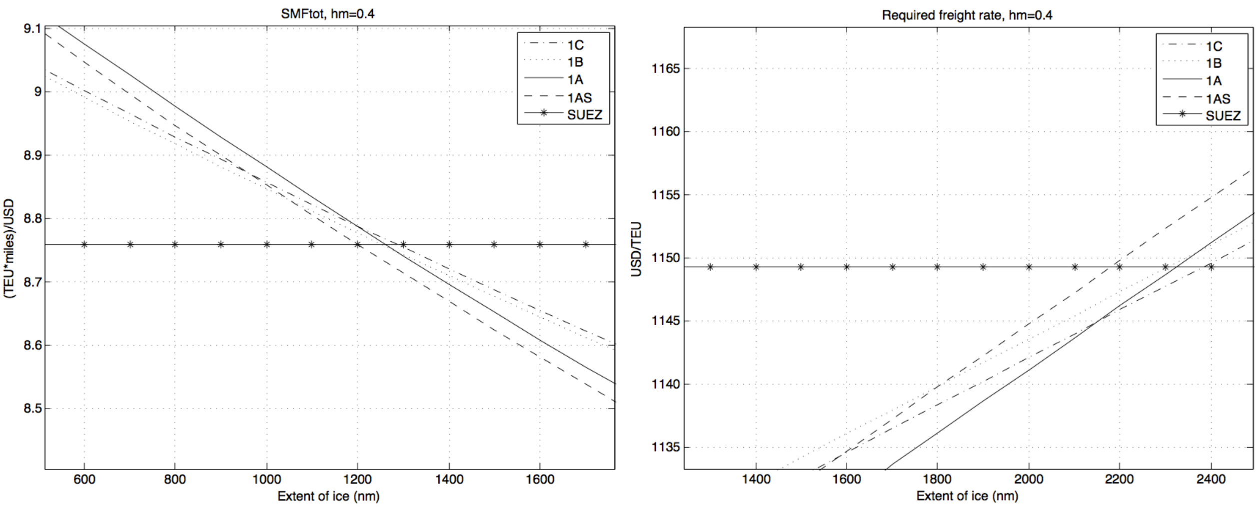


Figure 23: Sensitivity for ice extent (1)

The number of trips using the NSR is constant with 3 trips for ice class 1C and 1B and 4 trips for 1A and 1AS. Therefore, the change in ice extent will affect ice class 1A and 1AS the most which can bee seen in Figure 23 above. This is however not realistic, as the ship owner could choose to use the SCR when the ice conditions deteriorate. Nevertheless, the result is still valid for the respective number of trips. For brash ice thickness 0.4 meter, using the NSR is economically beneficial as long as the extent is less than 2200 nm for ice class 1A as displayed in Figure 23.

For brash ice thickness 0.8 meter, the resistance is higher and thus the potential economic profitability of using the NSR is more sensitive for increasing ice extent. As can be seen in Figure 24 below, ice class 1A is now the better choice compared to Suez when the ice extent is less than approximately 1300 nm, significantly less than for brash ice thickness 0.4 meter.

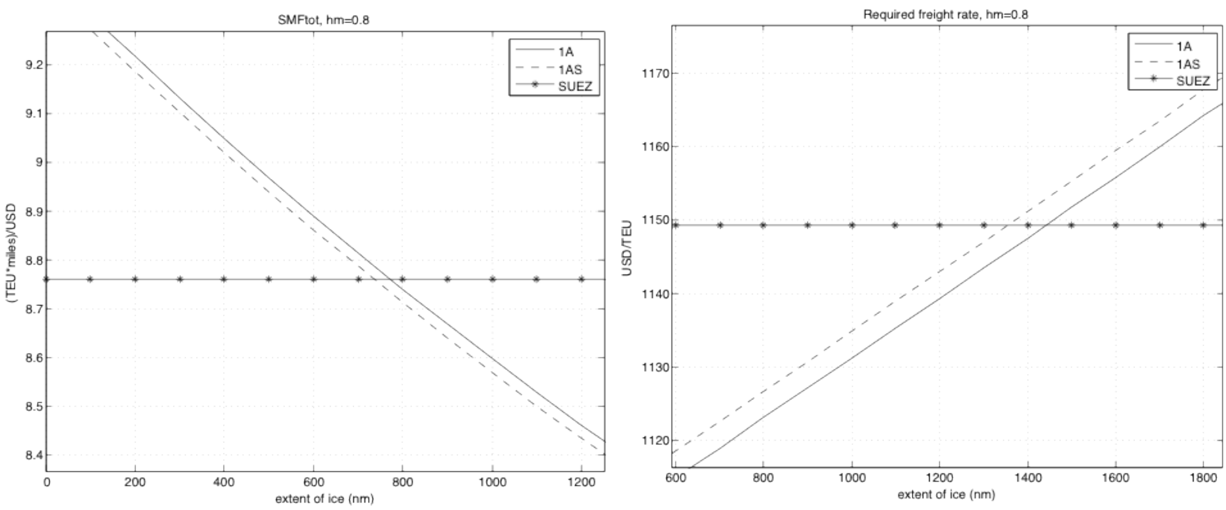


Figure 24: Sensitivity for ice extent (2)

6.2.5.3 Cost of Fuel

With fuel costs being one of the largest expenses for a ship operator, it is important for profitability.

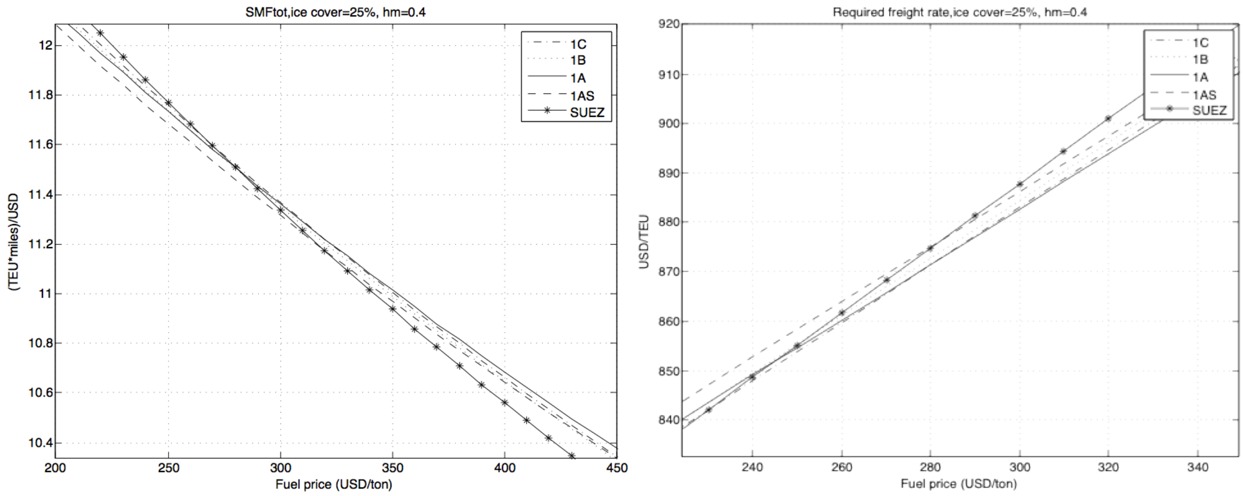


Figure 25: Sensitivity for altering fuel cost (1)

With fuel prices below approximately 250 USD/ton the Suez vessel is the best with respect to both the RFR and the SMF_t when ice is covering 25 % of NSR, see Figure 25. For the other ice scenario of 50 % ice cover and thicker ice, the Suez vessel shows better profitability when fuel prices are below 500 USD/ton as can be seen in Figure 26.

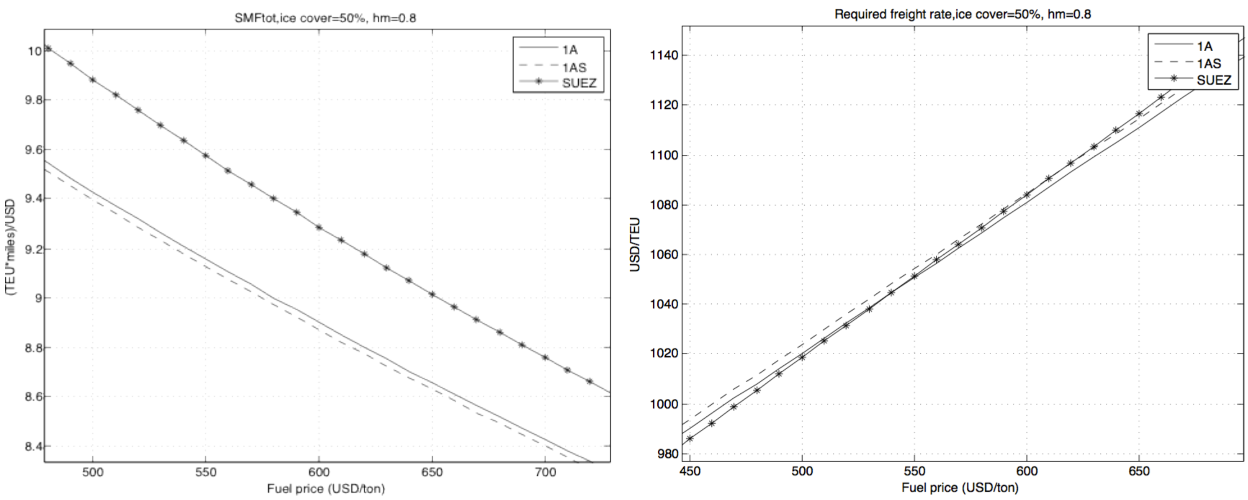


Figure 26: Sensitivity for altering fuel cost (2)

As shown in Figure 26, the SMF_t is less for the ice-classed vessels than the Suez for the fuel price range investigated, which was from 200 to 1200 USD/ton. The SMF_t for the ice-classed vessels are that low of the same reasons as described in section 6.2.4

When summarizing the above-discussed results, the 1A ice class vessels has the best performance followed by ice class 1C, both performing better than the SCR vessel by all calculated measures, and as shown, the design performance is significantly affected by the presence of ice. Currently ice class 1C is not allowed to navigate on the NSR, and its lower capability with respect to ice thickness makes it far less flexible with respect to what ice conditions it can navigate in.

6.3 Case 2: Optimizing Design for Schedule and Route

In this second case study, the possibility of optimizing the design of the vessel to fit the schedule and route of Case1 better and thus yield more profit is investigated. As earlier described, the vessel used in Case1 is a standard SCR vessel fitted with the required ice class and other necessary requirements to navigate the NSR. However, a vessel specifically designed for the purpose of navigating the East – West trade by utilizing the NSR in addition to the SCR will be more suited and better for the job.

A design, which uses both the SCR and the NSR, must be a compromise of two different worlds. It must fulfil the requirements of the NSR with ice and low temperatures, and at the same time be suited for navigating the SCR with low open water resistance and totally different temperatures. By altering the parameters of the ship merit factor an improved design as been developed.

The easiest way to improving the design would be to increase cargo capacity by increasing the ship size. This would be beneficial for the RFR as well, as a higher number annual cargo transported would cover the expenses. However, if assuming that the capacity and schedule is the same as in Case1, the design could still be optimized quite a bit.

6.3.1 Optimizing Hull Form

Designing the hull for the speed it operates the most in will be beneficial. Though, as the vessel navigates ice, and this distance is constantly changing, the average speed on the route changes as well. With the current schedule, the vessel navigates in 20 knots on the SCR, while on the NSR the average speed is approximately 13 knots if sailing in 1000 nm of 0.8 m thick brash ice.

With four trips on the NSR, the vessel operates 40 % of the time using the NSR, however the fraction that time spent in ice will vary significantly with the changing ice conditions. Nevertheless, the ship owner would not use the NSR if the ice conditions make it inefficient. Therefore, the new design speed is calculated as the weighted average based on four trips using the NSR with no ice, and the rest on the SCR, which is 17 knots.

With the design speed lowered, the hull lines could be altered in such a way that the vessel could accommodate more cargo and the cost would change as well, although this hard to quantify, and will not be elaborated in more detail in this thesis.

There are however several other alternatives for increasing the hull efficiency. First, the breadth of the vessel could be lowered; this would be beneficial for both brash ice resistance and open water resistance. Still, it must be considered with consideration on stability and longitudinal strength, as the vessel would need to be longer to compensate for the loss in cargo capacity.

Secondly, the correct hull form with regards to both brash ice and open water resistance should be decided with weight on the expected time in spent in ice versus open water. Here, perhaps the most important decision will be with regards to the design of the bow, where one can optimize the bow as a compromise from open water and brash ice resistance. These fine adjustments, are however difficult to measure with the SMF, mainly because the differences would be so small that more detailed calculations with regards to open water resistance and brash ice resistance should be conducted and implemented.

6.3.2 Propulsion Power

As the design speed has been lowered from 24 to 17 knots the installed power can be reduced as well. This will on the other hand decrease the performance in ice, but since the vessel mostly operates in open water, the maximum speed in open water should decide the engine size. With the engine being one of the largest purchase costs of a container vessel, reducing the engine size will reduce the cost of the vessel in addition to the weight.

Although the design speed has been lowered, the vessel should still have enough power to go faster when it need to keep schedule. As a result, the decrease in propulsion power cannot be too large. By using the container vessel statistics according to Levander (2009), the propulsion power is reduced from 35 MW to 28 MW, which should be enough to reach speeds of approximately 21 knots. Using an estimate of 400 USD/kW for two stroke low speed diesel engines as provided by Frouws, Stapersma, and Pinkster (2000), the cost savings of reducing propulsion power sums up to 3.2 M USD.

Other ways of increasing the SMF would be to amongst others, increasing the propulsion efficiency, decreasing costs, shortening port time and lowering resistance etc. However, these improvements are hard to measure, and their consequences on cost are equally uncertain, and have therefore not been elaborated in this thesis. The changed ship parameters are mentioned above, the other parameters are kept similar to Case1, and the results are therefore comparable. This second case study should be viewed as an example of how the DSM could be used to assess and measure design alternatives, rather than finding the perfect ship for use on the NSR in combination to the SCR.

6.3.3 Results Case 2

6.3.3.1 Performance in Ice

Figure 27, which display performance in ice, shows that, the reduced installed power decreases the performance in ice, and the design will not be able to reach as high speeds as in Case1.

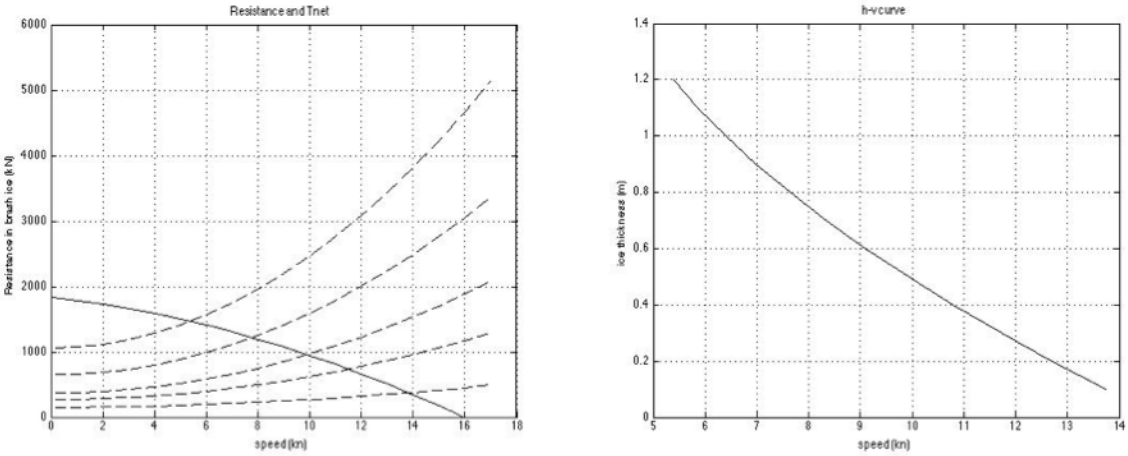


Figure 27: Calculated reistance, Tnet and h-v curve for optimized vessel

6.3.3.2 No Ice

As can be seen from the results below, the SMF_t has been increased quite significantly. Compared to the 1A ice class vessel in Case1, the SMF_t has been increased with approximately 12 %. When comparing with the 1A ice class vessel, the optimized version also shows marginally better performance measured through the LCC and RFR, as a result of the reduced engine cost. See Table 18.

Table 18: Results Case2 no ice

		NO ICE		
		SUEZ	**1A**	**1A Optimized**
LCC	USD	$489,490,000.00	$465,000,000.00	$461,000,000.00
RFR	USD/TEU	1149.30	1091.00	1083.30
SMF_{ow}	(TEU*mile)/USD	8.76	6.59	7.50
SMF_{ice}	(TEU*mile)/USD	0.00	2.80	3.19
SMF_t	(TEU*mile)/USD	8.76	9.39	10.68

Reducing the design speed to 17 knots while keeping the other parameters unaltered increases the SMF_t alone with almost 30 %. However, when reducing the design speed, one would also reduce the engine size and ship cost accordingly, as a result the SMF_t is decreased significantly.

6.3.4 Performance of Optimized Design in Ice

Due to the optimized design´s poorer performance in ice, the presence of ice will affect the results more than compared to the 1A ice class vessel of Case1. Thus, with increasing ice in terms of thickness and extent, the performance of the two 1A class vessels becomes more equal. As the Optimized vessel does not reach the same speed as the vessel of Case1, it must sail faster when not in ice, resulting in higher fuel costs. This is better seen in the detailed results presented by the fuel consumption in Appendix I.

Table 19: Results 25% ice extent, 0.4m brash ice thickness (Case2)

Ice extent= 25 %, hm= 0.4 m				
		SUEZ	**1A**	**1A Optimized**
LCC	USD	$489,490,000.00	$471,000,000.00	$469,000,000.00
RFR	USD/TEU	1149.30	1106.60	1100.40
SMF_{ow}	(TEU*mile)/USD	8.76	6.50	7.38
SMF_{ice}	(TEU*mile)/USD	0.00	2.57	3.00
SMF_{t}	(TEU*mile)/USD	8.76	9.06	10.38

The optimized vessel performs best in all measured results, even though the differences become less when the presence of ice increases a can be seen from Table 19 and Table 20. Judging by all calculated results, the optimized design is the one too choose of the three alternatives.

Table 20: Results 50% ice extent, 0.8m brash ice thickness (Case2)

Ice extent= 50 %, hm= 0.8 m				
		SUEZ	**1A**	**1A Optimized**
LCC	USD	$489,490,000.00	$486,000,000.00	$484,000,000.00
RFR	USD/TEU	1149.30	1141.40	1137.40
SMF_{ow}	(TEU*mile)/USD	8.76	6.30	7.14
SMF_{ice}	(TEU*mile)/USD	0.00	2.13	2.55
SMF_{t}	(TEU*mile)/USD	8.76	8.43	9.69

As shown through this second case study, the DSM can be used to assess design alternatives and optimize them in order to yield more profit. Having an optimized vessel for the specific route and schedule is important in order to maximize profit and additionally minimize emissions. For this specific case, improving the hull for the correct design speed and fitting the design to the schedule and route proved to enhance the design. The optimized 1A ice classed vessel is performing better by all measured results.

7 Discussion

Although the model seems to present reasonable results based on the specific input, there are some points where it could be improved and modified. Particularly the resistance in ice is quite uncertain, and the principle of super positioning as described by Juva and Riska (2002), has not been adopted as the resistance in ice looks to be sufficiently high. The equations used are the same as used for the power requirements of the FSICR, but there the speed is kept constant at 5 knots. No better method of predicting the brash ice resistance has been found, and the method nevertheless gives more a more accurate description of the experienced resistance than assuming a speed and resistance as done in other assessments of the NSR. In addition the model allows the user to modify the parameters of the design, in order to achieve the lowest possible brash ice resistance.

The open water resistance as used in the DSM is more or less valid for standard container vessels within the size range defined. However, if the DSM is used too assess alternatives with different hull shapes, for instance different bow alternatives, the resistance curve for each respective alternative should be incorporated in the model. For the vessel in the two case studies the difference in open water resistance is shown in Figure 18. Being as it is, the differences in the calculated results with respect to the SCR vessel and the vessels using NSR should be larger, especially in cases where the open water speed on the NSR is low as a result of less ice. For the optimized vessel in case 2, where the hull shape was optimized for a lower design speed, one would as well preferred to run new open water resistance calculations, as a result, the calculated results would have been different.

Currently the maintenance costs for the fraction served in ice are simply assumed to be the double of the open water maintenance costs, this could however be a rough assumption, though for the case studies here, where the vessels mainly operate in open water the additional cost is not more than approximately 3% for the vessels which makes 4 trips in the worst ice case scenario. Nevertheless, for a potential user of the DSM, the additional maintenance cost for ice could easily be incorporated based on own knowledge.

As mentioned the model takes the ice conditions into account by ice extent and thickness. However, the real ice conditions cannot be described simply by the two parameters, where growlers, icebergs and multi-year ice etc. are present. The ice modelled ice conditions should therefore be seen as a simplification, and one should account for some additional delays as a result of unexpected ice conditions.

Design performance is in general hard to quantify and measure, though the SMF_t shows results which are realistic based on the certain input, it mainly refers to the hydrodynamic aspects of ship design. The SMF_t can in addition be used to show the designs performance on a given schedule, which is what is done when used in the DSM, but here for a combination of two routes as presented by the SMF_t. As shown with the second case study, using a design suited and optimized for the schedule and operations can have significant impact on the designs success and economy.

Throughout several assessments, and recent voyages on the NSR the latest year, we know that using the NSR is technically feasible, at least during the summer months where ice is almost absent. However, this does not mean that the vessels do not need to be designed with ice navigation in mind as the ice conditions are changing rapidly. Thus, designing a vessel for the purpose of navigating on the NSR still remains a challenge.

Designing a vessel for operation on two very different routes such as the NSR and the SCR is a demanding task; especially the weighting of how much ice features and capability that should be incorporated in the design is difficult, partly as a result of the uncertain ice conditions. Finding the balance between ice and open water design feature is the key aspect of designing a vessel for this scenario, and the economic consequences of having an unbalanced design could be large.

The results of the case studies in this thesis are as in all other investigations, heavily dependent on the assumptions and input variables used. Particularly the building cost of the vessels are not based on any solid assessment, but in a shifting shipping industry, the prices of ships are fluctuating similarly, and the ones able to make the most profit are often those who are able to acquire ships the cheapest. This is exactly why using the DSM could be advantageous, as the different stakeholders have own assumptions and different cost basis. Hence, where using the NSR for one ship owner might be advantageous, it might not be so for others.

The additional weight of ice strengthening will decrease cargo capacity, however this has been overlooked in the case studies, mainly to keep the SMF valid. Though, with an increase in steel weight of approximately 15 % for ice class 1AS, which is a conservative estimate, the increase in weight would be 1950 tons when estimating from a steel weight of 13 000 tons. The weigh increase will then correspond to approximately 160 TEU if assuming an average TEU weight of 12 tons, which means that the cargo utilization must be higher then 96 % for this 3800 TEU vessel in order to have a loss in capacity. In addition, a container vessel is sensitive to volume, meaning they will usually fill up all container slots before reaching the weight constraint. Due to the high propulsion power and power plant of the vessel it is assumed that the ice classification will not increase the weight of the engines, gearboxes and shaft etc.

The differences in ice class and their respective operational time on the NSR heavily affects the results of the case study. While ice class 1B and 1C manages to make 3 trips using the NSR, and ice class 1A and 1AS 4 trips, the difference in operational time as based on the work of Erikstad and Ehlers (2012) is not that large. However, the difference with respect to ice capabilities are significantly higher, and the distinction on allowed operation with respect to ice thickness, might alone dictate whether one can use the NSR or not. The operational time will vary each year due to the changing ice conditions, and thus the annual operational time using the NSR will vary significantly from year to year almost independently on ice class.

As shown in the fist case study, investing in an ice classed vessel and using the NSR under the given assumptions will be more profitable than using only the SCR. However, the calculated benefit is not that large, and the potential user of the NSR should take into account the additional risk of operating in ice, together with uncertainty in ice conditions and resulting costs thereafter. Especially additional time and costs should be added due to the uncertainty, as the model does not take into other delaying features than presence of ice. In addition, many of the costs used are, as with the maintenance cost, uncertain. It is therefore necessary for the potential user of the DSM to have accurate input of costs and ship properties.

With 1A as the most profitable, which is currently the minimum requirement to be certain of allowance on the NSR, 1A seems to be the best alternative with respect to choice of ice class. The same hull is used for all ice classes in the first case study, which could be a rough assumption, as one would perhaps not have a open water bulb on a 1AS ice classed vessel. However, for a design that operates mainly in open water, fitting an open water bulb should be a good solution and its performance in brash ice should be acceptable. The capabilities with respect to ice thickness as discussed above also strengthens the conclusion of 1A as the preferred ice class, although, the future ice conditions and requirements of the NSR will dictate this choice.

As for the hull shape there are several alternative that could be evaluated for use on the NSR. There have already been build vessels specifically for the NSR that incorporate icebreaking bows and other features; the *SubArctic* 15,000 DWT ship (SA-15) series and the Russians even have a nuclear powered cargo vessel. Many of these vessels are however getting old, and many have been decommissioned. A newer development is the double acting ship (DAS), which by utilizing the benefit of the Azimuth propulsion system have great icebreaking capability when going astern first. The operator could simply build ice strengthened the vessels and depend on IB support as evaluated in the case studies. An alternative could be to have ice-breaking bow that will give a longer navigational period in the NSR and possibly paying a lower fee, but will have additional resistance in open water. The third alternative, which seems feasible, is to use DAS that will provide excellent icebreaking capability, good performance in open water but will be the most expensive to build. Which vessel type that will yield the most profit is of course dependent of the future ice conditions, fee on the NSR, fuel prices and building cost of the respective vessel types, and they are all interesting designs that could be assessed using the DSM.

Although the ice class rules set minimum power and strength requirements for ice classed vessels, and as shown in the second case study, a container vessel designed for high speeds on the SCR easily fulfils these requirements. There are however several propulsion and machinery layouts which could be evaluated when designing a vessel for the NSR. The most common machinery layout for ice-classed merchant tonnage is a setup of diesel engine(s) with direct shaft line and a fixed pitch propeller (FPP) or a controllable pitch propeller (CPP) (Riska, 2011a). The problem of the direct drive solutions for ice navigation is the narrow torque range of the diesel engine. This problem could however be solved by using a diesel-eclectic propulsion system, such as a Azimuth, which in addition to having a excellent torque range require much less machine room space. This solution can therefore increase the cargo capacity as well, especially valuable for volume sensitive vessels such as container vessels.

The thickness and presence of ice will dictate whether using the NSR will profitable or not, this has been investigated in the first case study and can be seen from the sensitivity calculations. The input used for the brash ice resistance as described in section 6.1.1, have been gathered from different sources, and are uncertain, particular those describing ice conditions and properties. However, these are taken to the best of knowledge, and the results could be different when these are changed, although most of them have little impact on resistance.

The ship size limitations on the NSR could be one of the largest hindrances for using the NSR as an addition or supplement to the SCR. The vessels operating the container trade East-West can be as large as up to 10 000 TEU and even larger, which is significantly larger than the vessel used in the case study here. The vessel used in the case studies is actually too large, being a capsize vessel, it is about 2 meter too wide, if using the supporting icebreakers width as a constraint. Still there might be a reason for using smaller vessels, being more flexible and adaptable they can serve ports and areas where the larger vessels cannot, and could therefore yield high profits, though, the schedule scenario as compared to the one used here, might then be different.

If the traffic on the NSR is to increase in the future, the need for assistance will grow as well, thus the size of the assisting fleet must correspond with the amount of traffic. Many of the Russian icebreakers are becoming old, and will soon be decommissioned. Based on this prospect the Russian government has decided to allocate 20 billion RUB to the building of new icebreakers (BARENTSNOVA, 2011). In addition a new icebreaker with breadth of 33 meter is to be build, allowing for larger vessels on the route (CHNL, 2012). Thus making it more competitive in comparison to the SCR.

One of major drawbacks of using the NSR today is the bureaucracy and uncertain channel fee of the NSR. The time to apply for NSR transit of 4 months ahead is in addition a great hinder of using the NSR as an alternative to the SCR. A ship operator should preferably be able to decide whether or not to use the NSR as late as when leaving port based on the latest ice and weather forecasts. Therefore, for the NSR to become a real option the bureaucracy must be reduced in addition the Russians must adopt a reasonable and stable fee policy that does not eliminate the savings of the reduced distance.

8 Conclusion

The global climate change continues to increase the marine transport in the Arctic Sea as a result of decreasing ice extends. The distinct conditions of the Arctic Sea, such as remoteness or the lack of marine infrastructure, represent a challenge to be surpassed in order to ensure safe and economical feasibility of the route. Furthermore, the assessment of the parameters and their sensitivity influencing the ship design for Arctic conditions, and thereby the safety of life at sea, are of outmost importance. Additionally, these design parameters required today and in the future for Arctic Sea transport need to be assessed with respect to their corresponding investment.

Therefore, a DSM have been developed which can be used to assess and support the decision to use the NSR or not, which take into account the encountered ice conditions and the vessels performance in the corresponding conditions with resulting resistance and fuel consumption thereafter. In addition, the DSM accounts for the investment cost of an ice classed vessel fulfilling the requirements, the different operational and voyage costs and the operational window on the NSR as result of ice class. Based on the above, the decision maker can asses the potential benefit of using the NSR from the calculated results from the DSM, which are, amongst others; the ship merit factor, the required freight rate and the life cycle cost

Together with the DSM a scenario of using the NSR in the summer season in addition to the SCR with a new built ice classed vessel has been presented. Different alternatives on how to combine the uncertain conditions on NSR with the strict and fixed schedule of liner shipping has been discussed; where slow steaming the NSR in the summer season and using the SCR for the rest of the year has been found to be the best alternative.

Based the current conditions on the NSR and requirements resulting from the environment on the route, together with the ice class requirements a summary of features that must be included in a design for the NSR has been developed. A ship design that are to combine the NSR and the SCR, must be a compromise, where the one must weight the incorporation of ice features based on the time spent in ice versus open water, the ice conditions themselves and keeping it as close as possible to open water design in order to remain commercially competitive.

Two case studies have been conducted using the developed DSM. In the first case study it is measured quantitatively how an SCR design will perform under the scenario as described above, when fitted with an ice class and fulfilling the other requirements to navigate the NSR. The Different ice classes of FSICR have been assessed for three different ice conditions, which have been differentiated by investment cost and operational time on the NSR.

Under the given assumptions and input used, all the FSICR classed vessels are more profitable using the NSR in the summer season than the same vessel without ice class navigating the SCR, consuming up to 60% less fuel compared to Suez. However, with the profitability declining as the ice extent and thickness grows, the dictating element deciding NSR profitability is the ice conditions. The 1A ice classed vessel have been found to be the best alternative of the FSICR vessels, also taking into consideration the ice capabilities of the 1A ice class with respect to ice thickness. The 1A ice class needs approximately 60 operational days on the NSR before profiting on the additional ice class investment for an ice extent of 1250 nautical miles with average thickness of 0.8 meter. Under the same ice conditions the 1A ice classed vessel have been found to be profitable as long as there is less than approximately 1500 nautical miles of ice on the NSR, and the fuel price higher than approximately 550 USD/ton fuel.

In the second case study, the possibility of optimizing the 1A ice class vessel of the first case study to fit the schedule and route better and thus yield more profit is investigated using the DSM. Therefore, the hull shape is altered to fit the lower speed of the schedule as used, which is represented by the design speed in the SMF calculations. With the design speed lowered, the propulsion power is reduced as well as the cost of the vessel.

Results of the second case study show that having an optimized vessel for the specific route and schedule is important in order to maximize profit and additionally minimize emissions. The optimized vessel shows better performance in all calculated results and ice scenarios, but are conversely more sensitive to ice extent as the propulsion power is lowered.

The economic advantage of using the NSR under the given scenario is however marginal, with the 1A-classed vessel needing on average approximately 40 USD less per TEU than the SCR vessel when there is no ice on all trips, and with increasing ice presence this difference becomes less with only 4 USD per TEU for the worst ice scenario. The potential user of the NSR must therefore take into account the additional risk and uncertainty of using the NSR, before making the final decision.

With increasing traffic over the recent year, it is well established that using the NSR is technically feasible. Nevertheless, in order to have shipping on the NSR on a regular basis, one must first and foremost have ice conditions that permit safe, economic and consistent navigation. Secondly, there must be a consistent fee system, which does not take away the benefit of the shorter distance in addition to shorter lead-time for booking NSR assistance. With these prerequisites in place, use of the NSR can be beneficial financially and in terms of reduced emissions.

9 Recommendation to Further Work

Currently the open water resistance curves must be implemented for every design. It is therefore suggested to implement a method of predicting the open water resistance as a result of the vessels input parameters, similarly to the brash ice resistance method used here. Furthermore, allowing for seasonal input of ice scenario, so that the time in ice will depend on the time of year could be implemented.

Moreover, an algorithm to find suitable design alternatives using optimization could be interesting with regards to finding more suitable designs, using an implemented open water resistance prediction method in combination to ice resistance prediction. Thereby, the design could better and quicker be optimized with regards to an operational profile for a vessel using NSR in addition to SCR.

References

AkerArctic. (2009). *History and development of Arctic Marine Technology*. FINLAND.

AMSA. (2009). Arctic Marine Shipping Assessment 2009 Report *Arctic Council, April 2009, second printing*.

BARENTSNOVA. (2011). Northern Sea Route gaining cargo turnover Retrieved 06.12.2011, 2011, from http://barentsnova.com/node/1554

Bertram, V. (2012). Practical Ship Hydrodynamics *Practical Ship Hydrodynamics (Second Edition)* (pp. iii). Oxford: Butterworth-Heinemann.

Borgerson, S. G. (2008). Arctic Meltdown: The Economic and Security Implications of Global Warming. *Foreign Affairs, 87*(2), 63-77.

Cariou, P. (2011). Is slow steaming a sustainable means of reducing CO2 emissions from container shipping? *Transportation Research Part D: Transport and Environment, 16*(3), 260-264. doi: 10.1016/j.trd.2010.12.005

CHNL. (2012). *Center For High North Logistics.* Paper presented at the CHNL 2012, Murmansk.

DNV. (2009). ARCON- Arctic Container Retrieved 01.04.2012, 2012, from http://www.dnv.com/industry/maritime/publicationsanddownloads/publications/dnvcontainershipupdate/2009/02/arcon.asp

Dodd, G. J. (1985). *Arctic Pilot* (7^{th} ed.).

Erikstad, S. O., & Ehlers, S. (2012). *A Decision Support Framework for Exploiting Northern Sea Route Transport Opportunities*. Paper presented at the COMPIT 2012, Liege- Belgium.

Frouws, J. W., Stapersma, D., & Pinkster, J. (2000). *Design of advanced Marine Vehicles*. Course material. Delft University of Technology, Marine Technology. DELFT, NETHERLANDS.

Finnish - Swedish ICE CLASS REGULATIONS 2008, 2530/30/2008 C.F.R. (2008).

Harries, S., Abt, C., Heinemann, J., & Hochkirch, K. (2006). Advanced hydrodynamic design of conatiner carriers for improved transport efficiency. In D. O. o. C. Ships (Ed.). London, UK.

IACS. (2011). Requirements concerning polar class: International Associaton of Classification Societies.

GUIDELINES FOR SHIPS OPERATING IN ARCTIC ICE-COVERED WATERS (2002).

INSROP. (2012). INSROP Overview Retrieved 12.03.2012, 2012, from http://www.fni.no/insrop/ - Overview

Jones, S. J. (2004). Ships In Ice - A review. Canada: Institute for Ocean Technology, National Research Council.

Juurmaa, K. (2006). Arctic Operational Platform (ARCOP Final Report).

Juva, M., & Riska, K. (2002). On the power requirements in the finnish-swedish ice class rules: Helsinki University of Technology.

Kaj Riska, M. W., Kim Eglund, Topi Leiviska. (1997). *Performance of merchant vessels in ice in the Baltic*. Espoo, December 1997: Helsinki University of Technology.

Kim, H. S. H., M. ; K. Ahn. D. ; Molyneux, D. (2006). Hull Form Designs For Icebreaking Tankers: Samsung Heavy Industries, Marine Research Institute, Institute for Ocean Technology, Naval Research Concil, CANADA.

Kon, Y. (2001). *The Northern Sea Route - The shortest sea route linking East Asia an Europe*. Tokyo, JAPAN: Ship and Ocean Foundation.

Lamb, T. (2004). Ship Design and Construction, Volumes 1-2 (pp. 40): Society of Naval Architects and Marine Engineers (SNAME).

Lasserre, F., & Pelletier, S. (2011). Polar super seaways? Maritime transport in the Arctic: an analysis of shipowners' intentions. *Journal of Transport Geography, 19*(6), 1465-1473. doi: 10.1016/j.jtrangeo.2011.08.006

Levander, K. (2009). *System Based Ship Design*. NTNU Marine Technology.

Lindqvist, G. (1989). A straightforward method for calculation of ice resistance of ships. *Proceedings of POAC 1989*, 722-735.

Liu, M., & Kronbak, J. (2010). The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. *Journal of Transport Geography, 18*(3), 434-444. doi: 10.1016/j.jtrangeo.2009.08.004

Mellor, M. (1980). Ship resistance in thick brash ice. *Cold Regions Science and Technology, 3*(4), 305-321. doi: 10.1016/0165-232x(80)90037-3

Nof, S. Y. (2009). *Springer Handbook of Automation*: Springer.

Nottebom, T. (2011). *Current Issues in Shipping, Ports and Logistics*: Uitgeverij UPA University Press Antwerp.

Notteboom, T. E., & Vernimmen, B. (2009). The effect of high fuel costs on liner service configuration in container shipping. *Journal of Transport Geography, 17*(5), 325-337. doi: 10.1016/j.jtrangeo.2008.05.003

Nowacki, H. (1985). Economic and technical issues in hull form developement.

Omre, A. (2012). An Economic Transport System for the Next Generation - Integrating the Northern and Southern Passages. Trondheim, Norway: NTNU.

Paik, J. K., & Thayamballi, A. K. (2007). Ship-Shaped Offshore Installations - Design, Building, and Operation: Cambridge University Press.

Polach, R. v. B. u., Janardanan, V., & Ehlers, S. (2012). *Ice model tests in context of the investment value of an offshore vessel*. Paper presented at the International Conference on Ocean, Offshore and Arctic Engineering, Rio de Janeiro, Brazil.

R. Bridges, S. H., MS. Kim, K. Riska. (2005). Current hull and machinery ice class rules requirements and impact of IACS Polar rules: Lloyds Register, Helsinki University of Technology.

Riska, K. (2011a). Design of Ice Breaking Ships. Course material NTNU 2011: ILS, OY, Helsinki, FINLAND and NTNU,Trondheim, NORWAY.

Riska, K. (2011b). Ship- Ice interaction in ship design: Theory and Practice. Course Material NTNU.

Riska, K., Wilhelmson, M., Eglund, K., & Leiviska, T. (1997). *Performance of merchant vessels in ice in the Baltic*. Espoo, December 1997: Helsinki University of Technology.

Rodrigue, J.-P. (2012). Maritime Container Freight Rates (USD per TEU), 1993-2209 Retrieved 04.03.2012, 2012, from http://people.hofstra.edu/geotrans/eng/ch7en/conc7en/maritimefreightrates.html

Schneekluth, H., & V, B. (2007). *Ship Design for Efficiency and Economy (2nd Edition)*: Elsevier.

Schøyen, H., & Bråthen, S. (2011). The Northern Sea Route versus the Suez Canal: cases from bulk shipping. *Journal of Transport Geography, 19*(4), 977-983. doi: 10.1016/j.jtrangeo.2011.03.003

Sodhi, D. S. (1995). Nothern Sea Route Reconnaissance Study - A summary of Icebreaking Technology. ALASKA: Cold Regions Research & Enigeering Laboratory.

Stopford, M. (2003). Maritime Economics - Second Edition T. Francis (Ed.)

Su, B., Riska, K., & Moan, T. (2010). A numerical method for the prediction of ship performance in level ice. *Cold Regions Science and Technology, 60*(3), 177-188. doi: 10.1016/j.coldregions.2009.11.006

Su, B., Riska, K., & Moan, T. (2011). Numerical study of ice-induced loads on ship hulls. *Marine Structures, 24*(2), 132-152. doi: 10.1016/j.marstruc.2011.02.008

Taylor, B. W. (2007). *Introduction to management science 9th ed.*: Pearson Prentice Hall.

Tschudi. (2010) Retrieved 05.12.11, 2011, from http://www.tschudiarctictransit.com

Requiremens for the design, equipment and supplies of vessels navigating the northern sea route (1990).

Vanebo, N. (2011). Analyserer Nordøstpassasjen. *Knutepunkt*.

Veritas, D. N. (2008). Ship Operations in cold Climate. Retrieved from http://www.dnv.com/industry/maritime/publicationsanddownloads/publications/variouspublications/arctic/index.asp

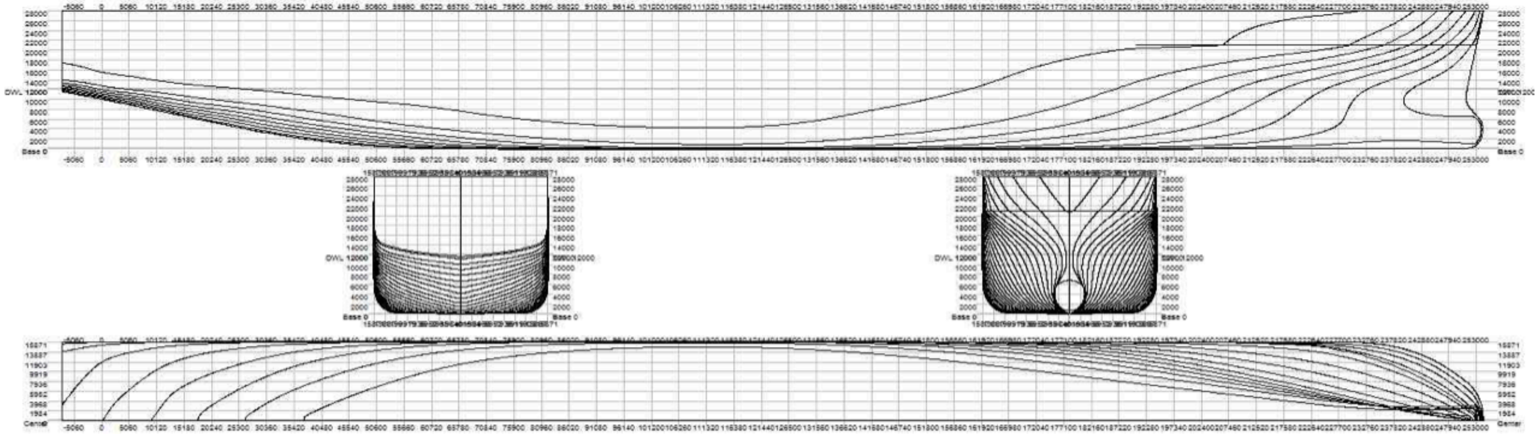
Verny, J. (2007). The importance of decoupling between the freight transport and ecnomic growth: the role of distnances. *European Journal of Transport and Infrastructure Research, 7 (2)*, 113-128.

Verny, J., & Grigentin, C. (2009). Container shipping on the Northern Sea Route. *International Journal of Production Economics, 122*(1), 107-117. doi: 10.1016/j.ijpe.2009.03.018

Wijnolst, N., & Wergeland, T. (2009). *Shipping Innovation*: Delft University Press.

Appendices

Appendix A: Design for case study



Design hydrostatics report.

container

Designer	sss
Created by	sss
Comment	
Filename	container.fbm

Design length	250.00 *(m)*	**Midship location**	125.00 *(m)*
Length over all	261.65 *(m)*	**Relative water density**	1.025
Design beam	32.000 *(m)*	**Mean shell thickness**	0.0000 *(m)*
Maximum beam	32.236 *(m)*	**Appendage coefficient**	1.0000
Design draught	12.000 *(m)*		

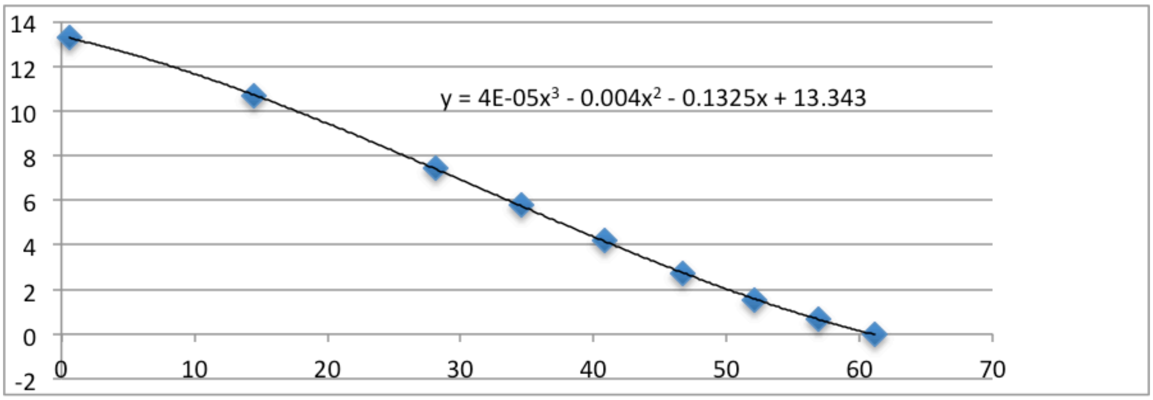
Volume properties		**Waterplane properties**	
Moulded volume	63668 *(m^3)*	Length on waterline	258.59 *(m)*
Total displaced volume	63668 *(m^3)*	Beam on waterline	32.232 *(m)*
Displacement	65260 *(tonnes)*	Entrance angle	85.747 *(Degr.)*
Block coefficient	0.6295	Waterplane area	6929.7 *(m^2)*
Prismatic coefficient	0.6567	Waterplane coefficient	0.8222
Vert. prismatic coefficient	0.7656	Waterplane center of floatation	107.38 *(m)*
Wetted surface area	10676 *(m^2)*	Transverse moment of inertia	524467 *(m^4)*
Longitudinal center of buoyancy	118.72 *(m)*	Longitudinal moment of inertia	28744656 *(m^4)*
Longitudinal center of buoyancy	-2.429 %		
Vertical center of buoyancy	6.719 *(m)*		
Total length of submerged body	261.48 *(m)*		
Total beam of submerged body	32.232 *(m)*		

Midship properties		**Initial stability**	
Midship section area	370.77 *(m^2)*	Transverse metacentric height	14.956 *(m)*
Midship coefficient	0.9586	Longitudinal metacentric height	458.20 *(m)*

Appendix B: Bow waterline area

Coordinates for bow section area

x	y
0.6	13.28
14.51	10.65
28.08	7.44
34.59	5.77
40.8	4.19
46.69	2.71
52.08	1.53
56.87	0.67
61.16	0




```
%Calculating waterline area of bow
x=0:1:61;

bow=@(x) (4E-05).*x.^3 - 0.004.*x.^2 - 0.1325.*x + 13.343;

bowarea=quad(bow,0,61)*2

fplot(bow,[0 61.16]); grid on;

%bow waterplane area= 806.47 m2
```

Appendix C: Power requirements of FSICR

For new ships, propulsion power must be more than, (FSICR, 2008);

$$P = K_e \frac{(R_{CH}/1000)^{3/2}}{D_P}[kW];$$

where K_e shall be taken as follows:

Propeller type or machinery	CP or electric or hydraulic propulsion machinery	FP propeller
1 propeller	2.03	2.26
2 propellers	1.44	1.60
3 propellers	1.18	1.31

These K_e values apply for conventional propulsion systems. Other methods may be used for determining the required power for advanced propulsion systems (see 3.2.4).

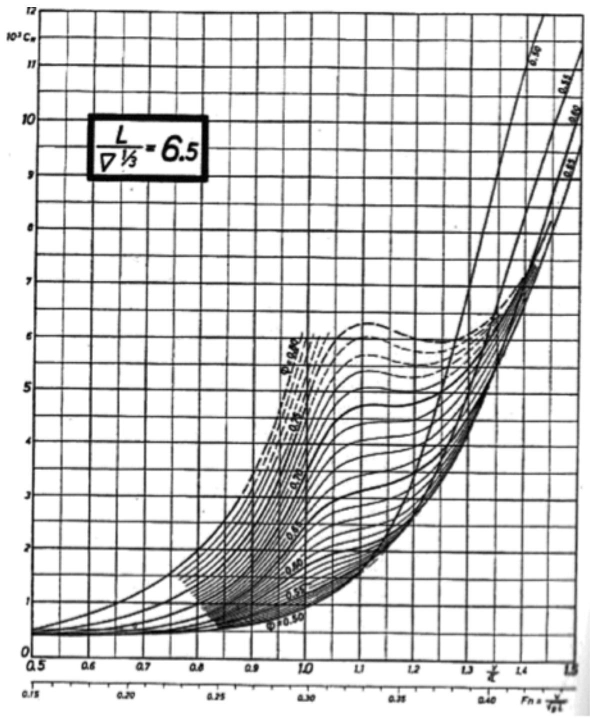
```
%Controlling propulsion power

Rch=493000; %N calculated brash ice resistance at 1m @ 5 knots
Ke=2.03;
Dp=7.5;

P=Ke*(Rch/1000)^(3/2) /Dp
```

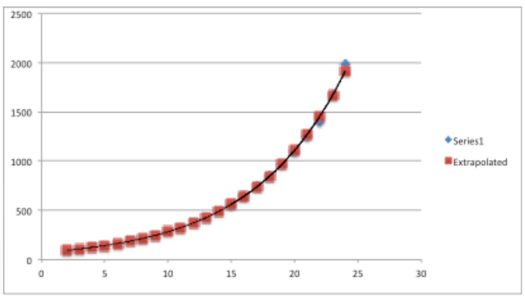
Appendix D: Resistance calculations for case study design

Resistance calculations
Guldhammer/Harvald
Ship data:

Lwl	258.6	m	
Beam (max)	30	m	
Design draught	12	m	
Displacement	65260	ton	
Displaced volume	63668	m^3	
Kinematic viscosity	1.35E-06	(m^2)/s	from ICCT http://ittc.sname.org/2002_recomm_proc/7.5-02-01-03.pdf
Density saltwater	1.025		
Slenderness ratio	6.5		
B/T	2.5	-	
Cm - Midship coefficient	0.9586	-	
Cp - Prismatic coefficient	0.6567	-	
Wetted surface	10676	m^2	

Speed [kn]	15	16	17	18	19	20	21	22	23	24
Speed [m/s]	7.716	8.2304	8.7448	9.2592	9.7736	10.288	10.8024	11.3168	11.8312	12.3456
Froudes number [-]	0.15	0.16	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.25
Reynolds numberl [-]	1.47E+09	1.57E+09	1.67E+09	1.77E+09	1.87E+09	1.97E+09	2.06E+09	2.16E+09	2.26E+09	2.36E+09
Resistance calculations										
Cf - Friction coeffisient (*10^3)	1.46	1.45	1.44	1.43	1.42	1.41	1.40	1.39	1.39	1.38
Cr - Table [-] (*10^3)	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.9	1.1
CA- Correction scale + rough [-] (*10^3)	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
Correction B/T [-] (*10^3)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Correction frame form	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Correction Bulb										
Total resistance [-] (*10^3)	1.71	1.75	1.79	1.83	1.87	1.91	1.95	1.99	2.19	2.38
Total resistance [kN]	557	648	748	857	977	1106	1246	1397	1675	1985





Appendix E: Ice class descriptions

Russian Maritime Register of Shipping Ice Classes

Ship category	Permitted thickness of ice, in m		Type of operation
	Independent navigation in open pack ice at a speed of 5 knots	Navigation in channel following an icebreaker in compact ice at a speed of 3 knots	
Ice1	0,40	0,35	Episodically
Ice2	0,55	0,50	Regularly
Ice3	0,70	0,65	Regularly

Ship category	Permitted speed, in knots	Ice concentration and type	Ice thickness, in m		Methods of surmounting ice ridges
			Winter/spring navigation	Summer/ autumn navigation	
Arc4	6 – 8	open floating first-year ice	0,6	0,8	Continuous motion
Arc5		open floating first-year ice	0,8	1,0	
Arc6		open floating first-year ice	1,1	1,3	
Arc7		close floating first-year ice	1,4	1,7	Episodic ramming
Arc8	10	close floating second-year ice	2,1	3,0	Regular ramming
Arc9	12	very close floating and compact multi-year ice	3,5	4,0	Surmount of ice ridges and episodic ramming of compact ice fields

Polar Class Description (IACS, 2011)

Polar Class	Ice Description (based on WMO Sea Ice Nomenclature)
PC 1	Year-round operation in all Polar waters
PC 2	Year-round operation in moderate multi-year ice conditions
PC 3	Year-round operation in second-year ice which may include multi-year ice inclusions.
PC 4	Year-round operation in thick first-year ice which may include old ice inclusions
PC 5	Year-round operation in medium first-year ice which may include old ice inclusions
PC 6	Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC 7	Summer/autumn operation in thin first-year ice which may include old ice inclusions

Equivalent notations for the Finnish-Swedish ice classes

Classification Society	Ice Class				
Finnish-Swedish Ice Class Rules	**IA Super**	**IA**	**IB**	**IC**	**Category II**
Russian Maritime Register of Shipping (Rules 1995)	UL	L1	L2	L3	L4
Russian Maritime Register of Shipping (Rules 1999)	LU5	LU4	LU3	LU2	LU1
American Bureau of Shipping	IAA	IA	IB	IC	D0
Bureau Veritas	IA SUPER	IA	IB	IC	ID
CASPPR, 1972	A	B	C	D	E
China Classification Society	Ice Class B1*	Ice Class B1	Ice Class B2	Ice Class B3	Ice Class B
Det Norske Veritas	ICE-1A*	ICE-1A	ICE-1B	ICE-1C	ICE-C
Germanischer Lloyd	E4	E3	E2	E1	E
Korean Register of Shipping	ISS	IS1	IS2	IS3	IS4
Lloyd's Register of Shipping	1AS	1A	1B	1C	1D
Nippon Kaiji Kyokai	*IA Super*	*IA*	*IB*	*IC*	*ID*
Registro Italiano Navale	IAS	IA	IB	IC	ID

Appendix F: Details for brash ice resistance calculations

3.2.1 Definitions

The dimensions of the ship and some other parameters are defined below:

L = length of the ship between the perpendiculars [m]

L_{BOW} = length of the bow [m]

L_{PAR} = length of the parallel midship body [m]

B = maximum breadth of the ship [m]

T = actual ice class draughts of the ship [m] according to 3.2.2

A_{wf} = area of the waterline of the bow [m^2]

α = the angle of the waterline at B/4 [degrees]

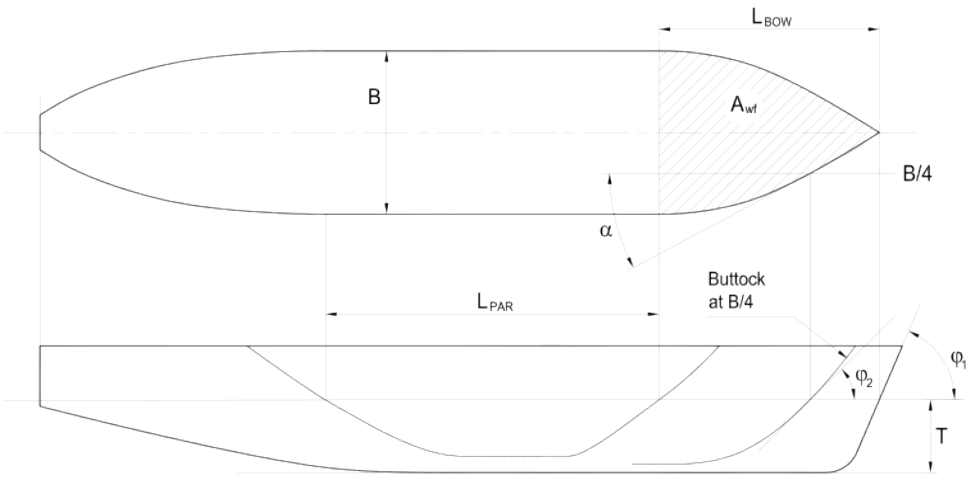
φ_1 = the rake of the stem at the centreline [degrees]

φ_2 = the rake of the bow at B/4 [degrees]

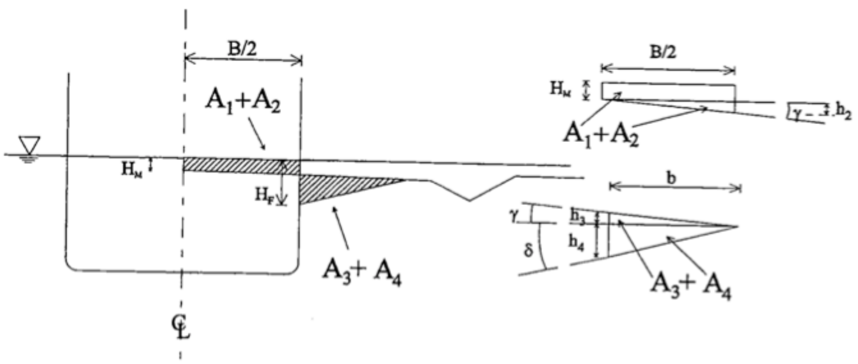
D_P = diameter of the propeller [m]

H_M = thickness of the brash ice in mid channel [m]

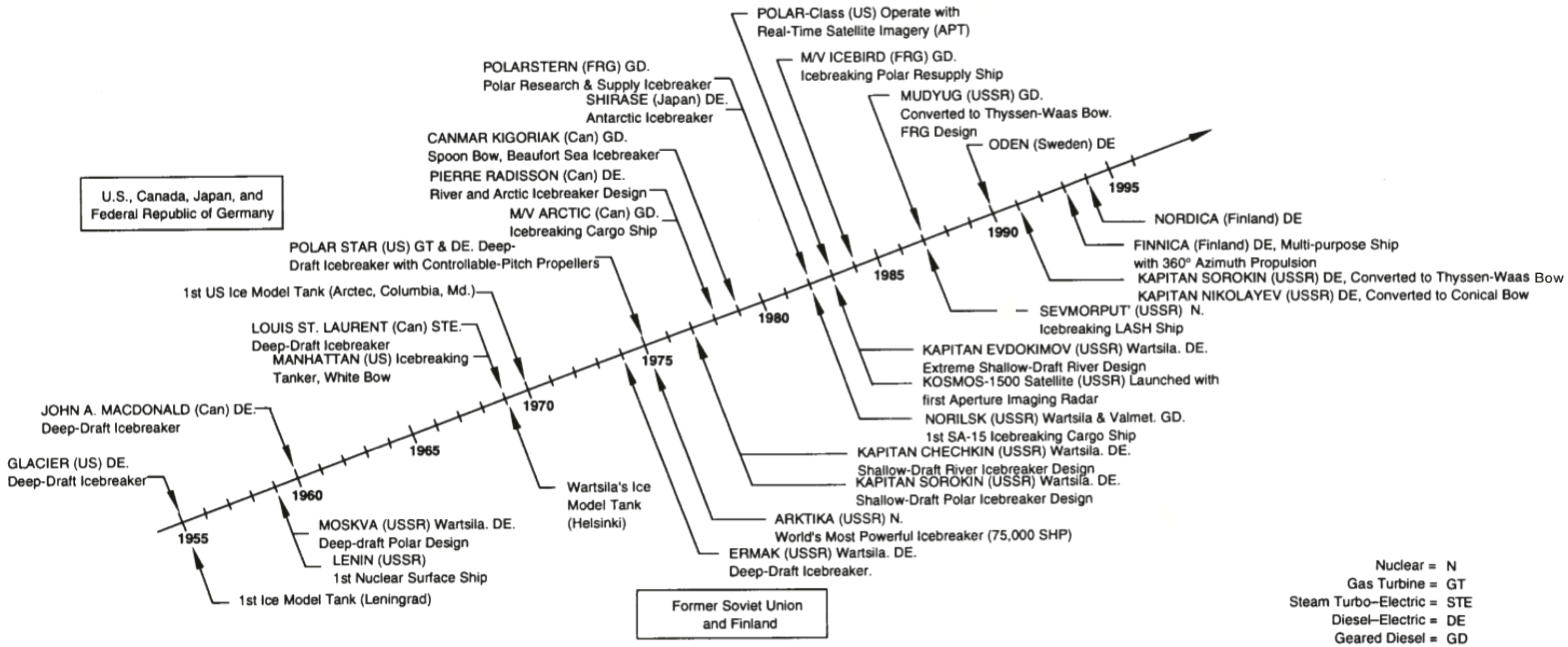
H_F = thickness of the brash ice layer displaced by the bow [m]



If bulb, then $\varphi_1 = 90°$



Appendix G: Evolution of Icebreaker technology and design



(Sodhi, 1995)

Appendix H: Results case study 1

		NO ICE				
		SUEZ	**1C**	**1B**	**1A**	**1AS**
Annual trips trough NSR	-	0.00	3.00	3.00	4.00	4.00
Annual trips trough SCR	-	14.00	11.00	11.00	10.00	10.00
Annual trips combined	-	14.00	14.00	14.00	14.00	14.00
Annual distance covered	nm	156520.00	145000.00	145000.00	141000.00	141000.00
Annual cargo carried	nm	39900.00	39900.00	39900.00	39900.00	39900.00
Annual bunker consumption on NSR	ton	0.00	0.00	0.00	0.00	0.00
Annual bunker consumption on SCR	ton	26080.00	20492.00	20492.00	18629.00	18629.00
Annual total bunker consumption in total	ton	26080.00	22721.00	22721.00	21601.00	21601.00
Annual bunker cost	USD	$ 18,256,000.00	$ 15,900,000.00	$ 15,900,000.00	$ 15,100,000.00	$ 15,100,000.00
Bunker cost pr nm	USD/nm	116.64	109.82	109.82	107.30	107.30
Annual CO2 emissions	ton	82674.00	72025.00	72025.00	68475.00	68475.00
Transporteff.	g(fuel)/ton*nm	0.35	0.33	0.33	0.32	0.32
Transporteff.	g(C02)/ton*nm	1.10	1.04	1.04	1.01	1.01
Annual cargo handling costs	USD	$ 5,985,000.00	$ 5,990,000.00	$ 5,990,000.00	$ 5,990,000.00	$ 5,990,000.00
Annual port costs	USD	$ 210,000.00	$ 210,000.00	$ 210,000.00	$ 210,000.00	$ 210,000.00
Annual crew wages	USD	$ 1,320,000.00	$ 1,320,000.00	$ 1,320,000.00	$ 1,320,000.00	$ 1,320,000.00
Annual shore crew cost	USD	$ 1,500,000.00	$ 1,500,000.00	$ 1,500,000.00	$ 1,500,000.00	$ 1,500,000.00
Annual cost of sales	USD	$ 3,990,000.00	$ 3,990,000.00	$ 3,990,000.00	$ 3,990,000.00	$ 3,990,000.00
Annual insurance and maintenense expences open water	USD	$ 6,560,000.00	$ 6,440,000.00	$ 6,440,000.00	$ 6,400,000.00	$ 6,400,000.00
Annual insurance and maintenense expences ice	USD	$ -	$ 120,000.00	$ 120,000.00	$ 160,000.00	$ 160,000.00
Annual capital costs	USD	$ 5,761,300.00	$ 5,760,000.00	$ 6,190,000.00	$ 6,310,000.00	$ 6,450,000.00
LCC	USD	$ 489,490,000.00	$ 466,000,000.00	$ 471,000,000.00	$ 465,000,000.00	$ 466,000,000.00
Required freight rate	USD/TEU	1149.30	1095.30	1106.10	1091.00	1094.60
Ship merit factor open water	(TEU*mile)/USD	8.76	7.22	7.15	6.59	6.57
Ship merit factor ice	(TEU*mile)/USD	0.00	2.09	2.07	2.80	2.79
Total ship merit factor	(TEU*mile)/USD	8.76	9.32	9.22	9.39	9.36

		Ice extent= 25 %, hm= 0.4 m				
		SUEZ	**1C**	**1B**	**1A**	**1AS**
Annual trips trough NSR	-	0.00	3.00	3.00	4.00	4.00
Annual trips trough SCR	-	14.00	11.00	11.00	10.00	10.00
Annual trips combined	-	14.00	14.00	14.00	14.00	14.00
Annual distance covered	nm	156520.00	145000.00	145000.00	141000.00	141000.00
Annual cargo carried	nm	39900.00	39900.00	39900.00	39900.00	39900.00
Annual bunker consumption on NSR	ton	0.00	251.84	251.84	251.84	251.84
Annual bunker consumption on SCR	ton	26080.00	20492.00	20492.00	18629.00	18629.00
Annual total bunker consumption in total	ton	26080.00	23277.00	23277.00	22342.00	22342.00
Annual bunker cost	USD	$ 18,256,000.00	$ 16,300,000.00	$ 16,300,000.00	$ 15,600,000.00	$ 15,600,000.00
Bunker cost pr nm	USD/nm	116.64	112.51	112.51	110.98	110.98
Annual CO2 emissions	ton	82674.00	73787.00	73787.00	70824.00	70824.00
Transporteff.	g(fuel)/ton*nm	0.35	0.34	0.34	0.33	0.33
Transporteff.	g(C02)/ton*nm	1.10	1.06	1.06	1.05	1.05
Annual cargo handling costs	USD	$ 5,985,000.00	$ 5,990,000.00	$ 5,990,000.00	$ 5,990,000.00	$ 5,990,000.00
Annual port costs	USD	$ 210,000.00	$ 210,000.00	$ 210,000.00	$ 210,000.00	$ 210,000.00
Annual crew wages	USD	$ 1,320,000.00	$ 1,320,000.00	$ 1,320,000.00	$ 1,320,000.00	$ 1,320,000.00
Annual shore crew cost	USD	$ 1,500,000.00	$ 1,500,000.00	$ 1,500,000.00	$ 1,500,000.00	$ 1,500,000.00
Annual cost of sales	USD	$ 3,990,000.00	$ 3,990,000.00	$ 3,990,000.00	$ 3,990,000.00	$ 3,990,000.00
Annual insurance and maintenense expences open water	USD	$ 6,560,000.00	$ 6,360,000.00	$ 6,360,000.00	$ 6,290,000.00	$ 6,290,000.00
Annual insurance and maintenense expences ice	USD	$ -	$ 275,000.00	$ 275,000.00	$ 373,000.00	$ 373,000.00
Annual capital costs	USD	$ 5,761,300.00	$ 6,140,000.00	$ 6,190,000.00	$ 6,310,000.00	$ 6,450,000.00
LCC	USD	$ 489,490,000.00	$ 475,000,000.00	$ 476,000,000.00	$ 471,000,000.00	$ 473,000,000.00
Required freight rate	USD/TEU	1149.30	1116.30	1117.80	1106.60	1110.30
Ship merit factor open water	(TEU*mile)/USD	8.76	7.09	7.08	6.50	6.48
Ship merit factor ice	(TEU*mile)/USD	0.00	1.91	1.91	2.57	2.56
Total ship merit factor	(TEU*mile)/USD	8.76	8.99	8.98	9.06	9.03

		Ice extent= 50 %, hm= 0.8 m		
		SUEZ	1A	1AS
Annual trips trough NSR	-	0.00	4.00	4.00
Annual trips trough SCR	-	14.00	10.00	10.00
Annual trips combined	-	14.00	14.00	14.00
Annual distance covered	nm	156520.00	141000.00	141000.00
Annual cargo carried	nm	39900.00	39900.00	39900.00
Annual bunker consumption on NSR	ton	0.00	731.79	731.79
Annual bunker consumption on SCR	ton	26080.00	18629.00	18629.00
Annual total bunker consumption in total	ton	26080.00	24174.00	24174.00
Annual bunker cost	USD	$ 18,256,000.00	$ 16,900,000.00	$ 16,900,000.00
Bunker cost pr nm	USD/nm	116.64	120.08	120.08
Annual CO2 emissions	ton	82674.00	76632.00	76632.00
Transporteff.	g(fuel)/ton*nm	0.35	0.36	0.36
Transporteff.	g(C02)/ton*nm	1.10	1.14	1.14
Annual cargo handling costs	USD	$ 5,985,000.00	$ 5,990,000.00	$ 5,990,000.00
Annual port costs	USD	$ 210,000.00	$ 210,000.00	$ 210,000.00
Annual crew wages	USD	$ 1,320,000.00	$ 1,320,000.00	$ 1,320,000.00
Annual shore crew cost	USD	$ 1,500,000.00	$ 1,500,000.00	$ 1,500,000.00
Annual cost of sales	USD	$ 3,990,000.00	$ 3,990,000.00	$ 3,990,000.00
Annual insurance and maintenense expences open water	USD	$ 6,560,000.00	$ 6,190,000.00	$ 6,190,000.00
Annual insurance and maintenense expences ice	USD	$ -	$ 586,000.00	$ 586,000.00
Annual capital costs	USD	$ 5,761,300.00	$ 6,310,000.00	$ 6,450,000.00
LCC	USD	$ 489,490,000.00	$ 486,000,000.00	$ 488,000,000.00
Required freight rate	USD/TEU	1149.30	1141.40	1145.10
Ship merit factor open water	(TEU*mile)/USD	8.76	6.30	6.28
Ship merit factor ice	(TEU*mile)/USD	0.00	2.13	2.12
Total ship merit factor	(TEU*mile)/USD	8.76	8.43	8.40

Appendix I: Results case study 2

		NO ICE		
		SUEZ	**1A**	**1A Optimized**
Annual trips trough NSR	-	0.00	4.00	4.00
Annual trips trough SCR	-	14.00	10.00	10.00
Annual trips combined	-	14.00	14.00	14.00
Annual distance covered	nm	156520.00	141000.00	141000.00
Annual cargo carried	nm	39900.00	39900.00	39900.00
Annual bunker consumption on NSR	ton	0.00	0.00	0.00
Annual bunker consumption on SCR	ton	26080.00	18629.00	18629.00
Annual total bunker consumption in total	ton	26080.00	21601.00	21601.00
Annual bunker cost	USD	$ 18,256,000.00	$ 15,100,000.00	$ 15,100,000.00
Bunker cost pr nm	USD/nm	116.64	107.30	107.30
Annual CO2 emissions	ton	82674.00	68475.00	68475.00
Transporteff.	g(fuel)/ton*nm	0.35	0.32	0.32
Transporteff.	g(C02)/ton*nm	1.10	1.01	1.01
Annual cargo handling costs	USD	$ 5,985,000.00	$ 5,990,000.00	$ 5,990,000.00
Annual port costs	USD	$ 210,000.00	$ 210,000.00	$ 210,000.00
Annual crew wages	USD	$ 1,320,000.00	$ 1,320,000.00	$ 1,320,000.00
Annual shore crew cost	USD	$ 1,500,000.00	$ 1,500,000.00	$ 1,500,000.00
Annual cost of sales	USD	$ 3,990,000.00	$ 3,990,000.00	$ 3,990,000.00
Annual insurance and maintenense expences open water	USD	$ 6,560,000.00	$ 6,400,000.00	$ 6,400,000.00
Annual insurance and maintenense expences ice	USD	$ -	$ 160,000.00	$ 160,000.00
Annual capital costs	USD	$ 5,761,300.00	$ 6,310,000.00	$ 6,000,000.00
LCC	USD	$ 489,490,000.00	$ 465,000,000.00	$ 461,000,000.00
Required freight rate	USD/TEU	1149.30	1091.00	1083.30
Ship merit factor open water	(TEU*mile)/USD	8.76	6.59	7.50
Ship merit factor ice	(TEU*mile)/USD	0.00	2.80	3.19
Total ship merit factor	(TEU*mile)/USD	8.76	9.39	10.68

		Ice extent= 25 %, hm= 0.4 m		
		SUEZ	**1A**	**1A Optimized**
Annual trips trough NSR	-	0.00	4.00	4.00
Annual trips trough SCR	-	14.00	10.00	10.00
Annual trips combined	-	14.00	14.00	14.00
Annual distance covered	nm	156520.00	141000.00	141000.00
Annual cargo carried	nm	39900.00	39900.00	39900.00
Annual bunker consumption on NSR	ton	0.00	251.84	259.46
Annual bunker consumption on SCR	ton	26080.00	18629.00	18629.00
Annual total bunker consumption in total	ton	26080.00	22342.00	22423.00
Annual bunker cost	USD	18256000.00	$ 15,600,000.00	$ 15,700,000.00
Bunker cost pr nm	USD/nm	116.64	110.98	111.38
Annual CO2 emissions	ton	82674.00	70824.00	71082.00
Transporteff.	g(fuel)/ton*nm	0.35	0.33	0.33
Transporteff.	g(C02)/ton*nm	1.10	1.05	1.05
Annual cargo handling costs	USD	$ 5,985,000.00	$ 5,990,000.00	$ 5,990,000.00
Annual port costs	USD	$ 210,000.00	$ 210,000.00	$ 210,000.00
Annual crew wages	USD	$ 1,320,000.00	$ 1,320,000.00	$ 1,320,000.00
Annual shore crew cost	USD	$ 1,500,000.00	$ 1,500,000.00	$ 1,500,000.00
Annual cost of sales	USD	$ 3,990,000.00	$ 3,990,000.00	$ 3,990,000.00
Annual insurance and maintenense expences open water	USD	$ 6,560,000.00	$ 6,290,000.00	$ 6,290,000.00
Annual insurance and maintenense expences ice	USD	$ -	$ 373,000.00	$ 373,000.00
Annual capital costs	USD	$ 5,761,300.00	$ 6,310,000.00	$ 6,000,000.00
LCC	USD	$ 489,490,000.00	$ 471,000,000.00	$ 469,000,000.00
Required freight rate	USD/TEU	1149.30	1106.60	1100.40
Ship merit factor open water	(TEU*mile)/USD	8.76	6.50	7.38
Ship merit factor ice	(TEU*mile)/USD	0.00	2.57	3.00
Total ship merit factor	(TEU*mile)/USD	8.76	9.06	10.38

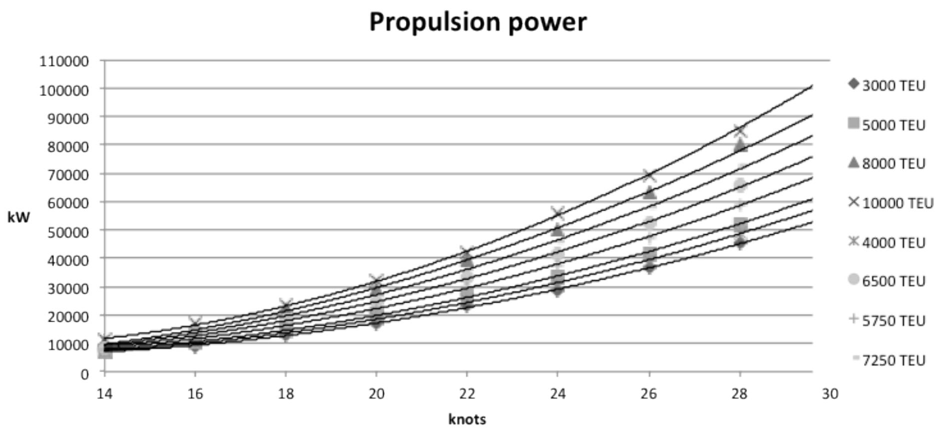
		Ice extent= 50 %, hm= 0.8 m		
		SUEZ	**1A**	**1A Optimized**
Annual trips trough NSR	-	0.00	4.00	4.00
Annual trips trough SCR	-	14.00	10.00	10.00
Annual trips combined	-	14.00	14.00	14.00
Annual distance covered	nm	156520.00	141000.00	141000.00
Annual cargo carried	nm	39900.00	39900.00	39900.00
Annual bunker consumption on NSR	ton	0.00	731.79	733.26
Annual bunker consumption on SCR	ton	26080.00	18629.00	18629.00
Annual total bunker consumption in total	ton	26080.00	24174.00	24384.00
Annual bunker cost	USD	$ 18,256,000.00	$ 16,900,000.00	$ 17,100,000.00
Bunker cost pr nm	USD/nm	116.64	120.08	121.12
Annual CO2 emissions	ton	82674.00	76632.00	77296.00
Transporteff.	g(fuel)/ton*nm	0.35	0.36	0.36
Transporteff.	g(C02)/ton*nm	1.10	1.14	1.15
Annual cargo handling costs	USD	$ 5,985,000.00	$ 5,990,000.00	$ 5,990,000.00
Annual port costs	USD	$ 210,000.00	$ 210,000.00	$ 210,000.00
Annual crew wages	USD	$ 1,320,000.00	$ 1,320,000.00	$ 1,320,000.00
Annual shore crew cost	USD	$ 1,500,000.00	$ 1,500,000.00	$ 1,500,000.00
Annual cost of sales	USD	$ 3,990,000.00	$ 3,990,000.00	$ 3,990,000.00
Annual insurance and maintenense expences open water	USD	$ 6,560,000.00	$ 6,190,000.00	$ 6,190,000.00
Annual insurance and maintenense expences ice	USD	$ -	$ 586,000.00	$ 586,000.00
Annual capital costs	USD	$ 5,761,300.00	$ 6,310,000.00	$ 6,000,000.00
LCC	USD	$ 489,490,000.00	$ 486,000,000.00	$ 484,000,000.00
Required freight rate	USD/TEU	1149.30	1141.40	1137.40
Ship merit factor open water	(TEU*mile)/USD	8.76	6.30	7.14
Ship merit factor ice	(TEU*mile)/USD	0.00	2.13	2.55
Total ship merit factor	(TEU*mile)/USD	8.76	8.43	9.69

Appendix J: Propulsion power for fuel consumption

FUELCONSUMPTION
Based on data from NOTTEBOOM

Speed	3000 TEU			4000 TEU			5000 TEU			5750 TEU			6500 TEU			7250 TEU			8000 TEU		10000 TEU	
knots	ton/day	kW	R kN	ton/day	kW	kN	ton/day	kW	kN	ton/day	kW	kN	ton/day	kW	kN	ton/day	kW	kN	ton/day	kW	ton/day	kW
14	33	7149	695	33	7149	695	33	7149	695	36	7843	762	39	8536	830	42	9229	897	45	9922	51	11214
16	42	9178	781	45	9970	848	49	10761	915	54	11751	999	58	12740	1084	63	13730	1168	67	14719	77	16894
18	58	12791	967	64	13978	1057	69	15165	1146	76	16749	1266	84	18333	1386	91	19918	1506	98	21502	107	23375
20	78	17193	1170	86	18777	1278	93	20360	1385	103	22538	1533	113	24715	1682	123	26892	1830	133	29070	147	32244
22	106	23180	1434	114	24962	1544	122	26743	1654	136	29911	1850	151	33078	2046	165	36246	2242	180	39413	191	41912
24	129	28376	1609	140	30750	1744	151	33125	1878	170	37382	2120	190	41639	2361	209	45896	2602	229	50154	255	55966
26	168	36738	1923	178	39113	2047	189	41488	2171	214	47032	2462	240	52576	2752	265	58120	3042	290	63664	316	69223
28	207	45499	2211	222	48664	2365	236	51829	2519	268	58858	2861	300	65887	3202	332	72915	3544	365	79944	387	84871
30	249	54649	2479	271	59399	2694	293	64149	2910	325	71274	3233	358	78399	3556	390	85524	3879	422	92649	482	105702

SFC	190	g/kwh
	0.000190	ton/kwh
	0.00456	ton/kw day
ploss	0.3	



Appendix K: Input parameters for DSM

```
clc; clear all;

%input for cost basis
sprintf('\n First, input for cost calculation must be inserted ')
cpayroll=input('Insert annual cost pr crewmember (USD) ');
cinsurance=input('Insert annual insurance cost for open water (USD) ');
cmaintenance=input('Insert annual maintenance cost (USD) ');
chfo=input('Insert price of heavy fuel oil in dollar pr ton ');
chandling=input('Insert price of cargo handling as USD per ton ');
csale=input('Insert cost of selling cargo as cost per ton ');
cportcall=input('Insert cost of port call as USD per GT ');
channelfee=input('Insert channel fee cost as USD pr passage');
ncrew=input('insert number of seagoing crew positions ');
npersposition=input('insert number of persons pr number of seagoing positions ');
npersonell=input('Insert number of shore personnel ');
cship=input('Insert purchase cost of ship ');
coverhead=input('Insert general overhead for ashore crew (%) ');
gearing=input('Insert loan percentage of purchase price (%) ');
interest=input('Insert interest rate on loan and for NPV calc (annual %) ');
shiplifetime=input('Insert estimated lifetime of vessel for linear depreciation
calculation (years) ');
loantime=input('Insert running time of loan (years) ');%insert a proper name here

%Additonal ice costs
cinsuranceice=input('Insert annual additional insurance cost related to ice navigation
(USD) '); %Additional annual insurance cost ? or pr trip?
icefee=input('Insert fee for icebreaking support etc pr passage (USD) \n\n');

%input for ship parameters
L=input('Insert length OA of vessel (m) ');
Lpar=input('Insert length of parallel midbody (m) ');
T=input('Insert draught of vessel (m) ');
B=input('Insert beam of vessel ');
displ=input('Insert displacement in ton of vessel (ton) ');
dwt=input('Insert deadweight in ton of vessel (ton) ');
payload=input('Insert design payload of vessel (ton) '); v
gtonnage=input('Insert gross tonnage of vessel ');
dspeed=input('Insert design speed in knots (knots) ');

%input relatet to ice resistance
Kp=input('Kp ');
hm=input('Insert average brash ice thickness in channel ');
phi=input('Insert, angle between the waterline and the vertical at B/4 ');
alpha=input('Insert stem angle, use 90 if bulb ');
uh=input('Insert the coefficient of friction between hull and ice');
K0=input('K0 ');
K=input('K');
Awf=input('Awf, insert area of waterline at bow (SEE FSICR) (m2) ');
Dp=input('Insert diameter of propeller (m)');

%input for machinery and fuel consumption
sprintf('\n\n Section for machinery and consumption ')
ppower=input('Insert maximum propulsion power (kW) ');
peff=input('Insert propulsion efficiency in open water ()');
peffice=input('Insert propulsion efficiency in ice ');
Ploss=('Insert loss from machinery to propeller (mechanical etc.)');
sfchfo=input('Insert specific fuel consumption for propulsion engine (g/kWh) ');

%input for cargo service
sprintf('\n\n section for cargo service ');
caputilization=input('Insert average capacity utilization (%) ');
Annualtrips=input('Insert annual number of trips for respective vessel');
Triptime=input('Insert length in time for each trip including port time (days)');
timeport=input('Insert average time for port call including arriving and departure
(hours) ');
```

```
wunit=input('Insert average weight pr TEU (ton) ');
ttot=365;
tice=input('Insert annual operating window for ice class (days) ');

%input for route
sprintf('\n\n Section for route input ');
donlyow=input('Insert distance of only open water route (nm) ');
dtotice=input('Insert distance of ice route in total  (nm) ');
dice=input('Insert distance in nm of part of route that is ice covered (nm) ');

disp('Now run script');
save input.mat
```

Appendix L: DSM matlab script

```
%COMPLETE WITH H-V CALCULATIONS
clc; clear all; load input.mat;
%H-V curve calculations

Tnet=zeros(1,dspeed+1); b=zeros(1,dspeed+1); c=[]; Kp=6.5;
psi=atand(tand(phi)/sind(alpha));
for Hm=[0.1,0.3,0.5,0.8,1.2]
    for v=(0:1:dspeed);
        if B>10 && Hm>0.4
           Hf=0.26+(B*Hm)^0.5;

Rch=0.5.*0.8.*150.*9.81.*Hf.^(2).*Kp.*(0.5+(Hm./(2.*Hf))).^(2).*(B+(2.*Hf).*...
           (cosd(22.6)-(1./tand(psi)))).*(uh.*cosd(phi)+sind(psi).*sind(alpha))...

+0.8.*150.*9.81.*K0.*uh.*Lpar.*Hf.^(2)+150.*9.81.*((L.*T./B.^2)).^3.*Hm.*Awf.*(v./sqrt(
9.81.*L)).^2;
        else

Hf=Hm+(B./2).*tand(2)+(tand(2)+tand(22.6)).*sqrt((B.*(Hm+(B./4).*tand(2))./(tand(2)+tan
d(22.6))));
           Rch=0.5.*0.8.*150.*9.81.*Hf^(2).*Kp.*(0.5+(Hm./(2.*Hf)))^(2)*(B+(2.*Hf).*...
           (cosd(22.6)-(1./tand(psi)))).*(uh.*cosd(phi)+sind(psi).*sind(alpha))...

+0.8.*150.*9.81.*K0.*uh.*Lpar.*Hf.^(2)+150.*9.81*((L.*T/B.^2)).^3.*Hm.*Awf.*(v./sqrt(9.
81.*L)).^2;
        end
         b(v+1)=Rch/1000;
    end
  c=[c;b];
end

Pd=ppower*0.8*(1-Ploss); %Delivered power 80 % MCR

for v=(1:dspeed-1);
    Tnet(v)=K*((Pd*Dp)^(2/3))*(1-((1/3)*(v/dspeed))-((2/3)*(v/dspeed)^(2)));
end

figure(1); r=0:1:dspeed; plot(r,c,'--k'); hold on; plot(r,Tnet,'k');
grid on; xlabel('speed (kn)'); ylabel('Resistance in brash ice (kN)')
title('Resistance and Tnet'); hold off;

c1=c(1,:); c2=c(2,:); c3=c(3,:); c4=c(4,:); c5=c(5,:);
t=polyfit(r,Tnet,2); t1=t(1); t2=t(2); t3=t(3);

d=polyfit(r,c1,2); d1=d(1); d2=d(2); d3=d(3); syms x;
dx=solve('d1*x^2 + d2*x + d3 = t1*x^2 + t2*x + t3'); cd1=subs(dx);
e=polyfit(r,c2,2); e1=e(1); e2=e(2); e3=e(3);
ex=solve('e1*x^2 + e2*x + e3 = t1*x^2 + t2*x + t3'); ce1=subs(ex);
f=polyfit(r,c3,2); f1=f(1); f2=f(2); f3=f(3);
fx=solve('f1*x^2 + f2*x + f3 = t1*x^2 + t2*x + t3'); cf1=subs(fx);
g=polyfit(r,c4,2); g1=g(1); g2=g(2); g3=g(3);
gx=solve('g1*x^2 + g2*x + g3 = t1*x^2 + t2*x + t3'); cg1=subs(gx);
h=polyfit(r,c5,2); h1=h(1); h2=h(2); h3=h(3);
hx=solve('h1*x^2 + h2*x + h3 = t1*x^2 + t2*x + t3'); ch1=subs(hx);

hh=[0.1,0.3,0.5,0.8,1.2]; vhice=[cd1(1),ce1(1),cf1(1),cg1(1),ch1(1)]; figure(2)
hh2=0.1:.1:1.2; vh=spline(hh,vhice,hh2);
hvi=polyfit(hh2,vh,2); vice=hvi(1).*hh2.^2+hvi(2).*hh2+hvi(3);
plot(vice,hh2,'k'); hold on; grid on; title('h-v curve');
xlabel('speed (kn)'); ylabel('ice thickness (m)');

if dice>0;
    vi= hvi(1)*hm^2 + hvi(2)*hm + hvi(3);
```

```
else
    vi=0;
end

%Service schedule calculations
if tice>0;
    dowice=dtotice-dice; %distance of open water on ice route
else
    dowice=0;
end
timesea=Triptime-(timeport/24); %time available for navigating
toperating=Triptime*Annualtrips; %Operating time
vow=donlyow./(timesea.*24); %speed in open water (not slow steaming)
Ttot=Annualtrips.*timesea; % Available time (days)
tripsiceroute=tice./(timesea); %days/days
tripsnoiceroute=(Ttot-tice)./timesea; %days/days
if dice>0 && tice>0
    ticewater=dice./vi; %Time in ice for each trip(hours)
else
    ticewater=0;
end

if tice>0;
    vowi=dowice./(timesea.*24-ticewater); %Speed slow steaming ice route
else
    vowi=0;
end

if tice>0;
    towice=dowice./vowi; %time slow steaming (hours)
else
    towice=0;
end

ttoticeroute=tice; % total time for ice route (days)
ttotnoiceroute=(Ttot-tice); % total time for route with no ice (days)
totalannualtrips=tripsiceroute+tripsnoiceroute;
annualdisticeroute=tripsiceroute*(dice+dowice);
annualdistancenoiceroute=tripsnoiceroute.*donlyow;
dtotalannual=annualdisticeroute+annualdistancenoiceroute;
cargoonboard=(caputilization./100).*payload;
annualcargocarried=cargoonboard.*totalannualtrips;
distanceice=dice.*tripsiceroute; %annual distance in ice
distanceslow=donlyow.*tripsiceroute; %annual distance slow steaming open water
distanceow=dowice.*tripsiceroute+donlyow.*tripsnoiceroute;

%Propulsion power for open water
if payload>=1500&&payload<3500 %payload refers to number of TEU
    averageservicepower=1164.3*(exp(1)).^(0.1296.*vow); %averageservice power (kW) 3000
elseif payload>3500&&payload<4500
    averageservicepower=1197.5*(exp(1)).^(0.1315.*vow); %4000
elseif payload>4500&&payload<5500
    averageservicepower=1227.9*(exp(1)).^(0.1333.*vow); %5000
elseif payload>5500&&payload<6250
    averageservicepower=1309.1*(exp(1)).^(0.1353.*vow); %5750
elseif payload>6250&&payload<6750
    averageservicepower=1392*(exp(1)).^(0.1368*vow); %6500
elseif payload>6750&&payload<7750
    averageservicepower=1476.2*(exp(1)).^(0.1383.*vow); %7250
elseif payload>5500&&payload<9000
    averageservicepower=1561.4*(exp(1)).^(0.1394.*vow); %8000
elseif payload>9000&&payload<=11000
    averageservicepower=1785.5*(exp(1)).^(0.1378.*vow); %10 000
else
    disp('Does not support payload size, rage must be from 1500 to 11000 TEU'); pause;
end

%Propulsion power for slow steaming in open water:
if payload>=1500&&payload<3500 %payload refers to number of TEU
```

```
    slowsteamingpower=1164.3*(exp(1)).^(0.1296.*vowi); %(kW) 3000
elseif payload>3500&&payload<4500
    slowsteamingpower=1197.5*(exp(1)).^(0.1315.*vowi); %4000
elseif payload>4500&&payload<5500
    slowsteamingpower=1227.9*(exp(1)).^(0.1333.*vowi); %5000
elseif payload>5500&&payload<6250
    slowsteamingpower=1309.1*(exp(1)).^(0.1353.*vowi); %5750
elseif payload>6250&&payload<6750
    slowsteamingpower=1392*(exp(1)).^(0.1368*vowi); %6500
elseif payload>6750&&payload<7750
    slowsteamingpower=1476.2*(exp(1)).^(0.1383.*vowi); %7250
elseif payload>5500&&payload<9000
    slowsteamingpower=1561.4*(exp(1)).^(0.1394.*vowi); %8000
elseif payload>9000&&payload<=11000
    slowsteamingpower=1785.5*(exp(1)).^(0.1378.*vowi); %10 000
else
    disp('Does not support payload size, rage must be from 1500 to 11000 TEU'); pause;
end

%Brash ice resistance (kN)
if B>10 && hm>0.4
   Hf=0.26+(B*hm)^0.5;
   Rch=(0.5.*0.8.*150.*9.81.*Hf.^(2).*Kp.*(0.5+(hm./(2.*Hf))).^(2).*(B+(2.*Hf).*...
   (cosd(22.6)-(1./tand(psi)))).*(uh.*cosd(phi)+sind(psi).*sind(alpha))...

+0.8.*150.*9.81.*K0.*uh.*Lpar.*Hf.^(2)+150.*9.81.*((L.*T./B.^2)).^3.*hm.*Awf.*(vi./sqrt
(9.81.*L)).^2)./1000;
else

Hf=hm+(B./2).*tand(2)+(tand(2)+tand(22.6)).*sqrt((B.*(hm+(B./4).*tand(2))./(tand(2)+tan
d(22.6))));
   Rch=(0.5.*0.8.*150.*9.81.*Hf^(2).*Kp.*(0.5+(hm./(2.*Hf)))^(2)*(B+(2.*Hf).*...
   (cosd(22.6)-(1./tand(psi)))).*(uh.*cosd(phi)+sind(psi).*sind(alpha))...

+0.8.*150.*9.81.*K0.*uh.*Lpar.*Hf.^(2)+150.*9.81*((L.*T/B.^2)).^3.*hm.*Awf.*(vi./sqrt(9
.81.*L)).^2)./1000;
end

%Bunker comsumption
Rslow=(slowsteamingpower.*(1-Ploss))/(vowi*0.5144); %Resistance when slowsteaming
Row=(averageservicepower.*(1-Ploss))/(vow*0.5144); %Resistance for no ice route
%Consumption ice
if dice>0
    consumptionice=(sfchfo.*ticewater.*ppower*0.8)./(1*10^6); % (ton)
else
    consumptionice=0;
end
%consumption slowsteaming
if tice>0
    consumptionslow=(sfchfo.*towice.*slowsteamingpower)./(1*10^6) ; %(ton)
else
    consumptionslow=0;
end
%consumption open water route
comsumptionopenwaterroute=(sfchfo.*ttotnoiceroute.*24.*averageservicepower)./(1*10^6);
%Total for both routes:
annualbunkerconsumption=consumptionice.*tripsiceroute...
    +comsumptionopenwaterroute+consumptionslow.*tripsiceroute;
annualbunkercost=annualbunkerconsumption.*chfo;
bunkercostprnm=annualbunkercost./dtotalannual;

%Emissions
CO2factor=3.17;
annualco2consumption=CO2factor*annualbunkerconsumption;
transporteffuel=(annualbunkerconsumption*10^6)/(annualcargocarried*dtotalannual*wunit);
%g [g fuel/ton*nm]
transporteffc02=transporteffuel*CO2factor; % [g CO2/ton*nm]

%costs
```

```
cargohandlingcost=chandling.*annualcargocarried;
portcost=cportcall.*totalannualtrips*gtonnage;
crewwages=cpayroll.*ncrew*nperposition;
shorepersonellcost=npersonell.*cpayroll.*(coverhead/100);
costsales=csale.*annualcargocarried;
cexpensesow=cinsurance*tripsnoiceroute+((cmaintenance*distanceow)/dtotalannual);

%maintenance and insurance for ice route
if tice>0

cexpensesice=cinsuranceice*tripsiceroute+((cmaintenance.*2.*distanceice)./dtotalannual)
;
else
    cexpensesice=0;
end
% Channel fee Suez Canal
tot_net_tonnage=payload*wunit;
cfee=(5000*7.21+5000*6.13+10000*3.37+20000*2.42+((tot_net_tonnage-40000)*2.42))...
    *tripsnoiceroute;
cicefee=icefee.*tripsiceroute;

%Capital costs for first year
annualshipdepcost=80./shiplifetime;
annualrepayments=(equity./100).*cship*(interest./100)*((1+(interest./100))...
    .^loantime)/((1+(interest./100)).^loantime-1); %includes annual backpayments and
interest;;
capitalcosts=annualrepayments+((annualshipdepcost./100).*cship);
grossrevenue= cargohandlingcost+portcost+crewwages+provisions+shorepersonellcost...
    +costsales+cexpensesow+cexpensesice+capitalcosts+cfee+cicefee;

%RFR
cannualrunning=cargohandlingcost+portcost+crewwages+shorepersonellcost...
    +costsales+cexpensesow+cexpensesice+cfee+cicefee+annualbunkercost+capitalcosts;
LCC=cannualrunning*((1+(interest/100))^shiplifetime-
1)/((interest/100)*(1+(interest/100))^shiplifetime);
npvrate=((1+(interest/100))^shiplifetime-
1)/((interest/100)*(1+(interest/100))^shiplifetime);
revenue=LCC/npvrate;
RFR=revenue/annualcargocarried;

%SMF
convfactor=8760;
aac=cargohandlingcost+portcost+crewwages+shorepersonellcost+costsales+cexpensesow+...
    cexpensesice+capitalcosts+cfee+cicefee+annualbunkercost;
utilizationfactor=toperating./ttot;

%SMFow
operatingspeedfactor=vow./dspeed;
porttimefactor=ttotnoiceroute./toperating;
k=(convfactor*utilizationfactor.*(caputilization./100)*operatingspeedfactor).*porttimef
actor;
smfow=k.*(ppower./aac).*(payload./Row).*peff;

%SMFice
operatingspeedfactorice=((vowi.*dowice+vi.*dice)/(dice+dowice))/dspeed;
porttimefactorice=ttoticeroute./toperating;
kice=(convfactor*utilizationfactor.*(caputilization./100)*operatingspeedfactorice).*por
ttimefactorice;
Rice=(Rch*dice+dowice*Rslow)./(dice+dowice);
pice=(peffice*dice+dowice.*peff)./(dice+dowice); %Propeller efficiency ice as fucntion
of fraction served in ice
if tice>0
    smfice=kice.*(ppower./aac).*(payload./Rice).*pice;
else
    smfice=0;
end
%SMFtot
smftot=smfow + smfice;
```

```
%PRINT
out=fopen('results','wt');
pservices=[tripsiceroute;tripsnoiceroute;totalannualtrips;dtotalannual;annualcargocarri
ed];
sprintf(' Service Schedule')
sprintf(' Annual trips trough ice route = %23.0f \n Annual trips trough open water
route = %20.0f \n Annual trips combined = %29.0f \n Annual distance covered = %27.0f \n
Annual cargo carried = %30.0f TEU ', pservices)
fprintf(out,' Annual trips trough ice route = %23.0f \n Annual trips trough open water
route = %20.0f \n Annual trips combined = %29.0f \n Annual distance covered = %27.0f \n
Annual cargo carried = %30.0f TEU \n\n', pservices);
pbunker=[consumptionice;comsumptionopenwaterroute;annualbunkerconsumption;...

annualbunkercost;bunkercostprnm;annualco2consumption;transporteffuel;transporteffc02];
sprintf(' Bunker ')
sprintf(' Bunker consumption on ice route = %1.0f ton \n Bunker consumption on open
water route = %1.f ton \n Annual total bunker consumption = %1.f ton \n Annual bunker
cost = %1.0f USD \n Bunker cost pr nm = %1.0f ton/nm \n Annual CO2 emissions = %1.0f
ton \n Transporteff. = %1g [g(fuel)/ton*nm] \n Transporteff. = %1g [g(Co2)/ton*nm]
',pbunker)
fprintf(out,' Annual bunker consumption on ice route = %1.0f ton \n Annual bunker
consumption on open water route = %1.f ton \n Annual total bunker consumption = %1.f
ton \n Annual bunker cost = %1.0f USD \n Bunker cost pr nm = %1.0f ton/nm \n Annual CO2
emissions = %1.0f ton \n Transporteff. = %1g [g(fuel)/ton*nm] \n Transporteff. = %1g
[g(Co2)/ton*nm] \n\n',pbunker);
pcosts=[cargohandlingcost;portcost;crewwages;shorepersonellcost;costsales;cexpensesow;c
expensesice;capitalcosts;LCC];
sprintf(' Annual cargo handling costs = %1.0f USD \n Annual port costs = %1.0f USD \n
Annual crew wages = %1.0f USD \n Annual shore crew cost = %1.0f USD \n Annual cost of
sales = %1.0f USD \n Annual insurance and maintenance expenses open water route = %1.0f
\n Annual insurance and maintenance expenses ice route = %1.0f \n Annual capital costs
= %1.0f \n LCC = %1.0f ',pcosts)
fprintf(out,' Annual cargo handling costs = %1.0f USD \n Annual port costs = %1.0f USD
\n Annual crew wages = %1.0f USD \n Annual shore crew cost = %1.0f USD \n Annual cost
of sales = %1.0f USD \n Annual insurance and maintenance expenses open water route =
%1.0f \n Annual insurance and maintenance expenses ice route = %1.0f \n Annual capital
costs = %1.0f \n LCC = %1.0f ',pcosts);
rfr=RFR;
sprintf(' Required freight rate = %1.0f USD/TEU \n ',rfr)
smf=[smfow;smfice;smftot];
sprintf(' Ship merit factor open water = %1g \n Ship merit factor ice = %g \n Total
ship merit factor = %1g ', smf)
fprintf(out,' Ship merit factor open water = %g \n Ship merit factor ice = %g \n Total
ship merit factor = %g ', smf);
xlswrite('results',[pservices;pbunker;pcosts;rfr;smf]);
fclose('all');
save input.mat
sprintf('done')
```