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A simulation-based decision support tool for arctic transit transport

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Preface

This master thesis is completing my work for the Master of Science degree at the Vienna University of Technology (TU Wien) and was carried out under co-supervision of the Sustainable Arctic Sea Transport Research Group at the Marine Technology Department of the Norwegian University of Science and Technology (NTNU) in Norway. Part of this master thesis was therefore written during a stay abroad in summer semester 2014 and winter semester 2014/15 at NTNU in Trondheim, Norway.

The purpose of this thesis is to develop a simulation-based decision-support (SBDS) tool to support stakeholders in the decision making process of integrating arctic routes in the transport system. The developed tool has the capability to evaluate the economic feasibility of different route options and deal with the related uncertainties in input variables like climate development.

Abstract

The Russian Federation attempts to foster the Northern Sea Route (NSR) as a transport alternative to the current Suez Canal Route (SCR). Hence, ship operators and owners face the challenge of assessing whether the NSR might be economically advantageous for them. In order to support them in this complex task of comparing the economic feasibility of the joint use of the above-mentioned routes, this thesis presents a simulation-based decision-support (SBDS) tool. The SBDS-tool is carried out in two main steps, where in the first step for a specific vessel and route specific ice data the correspondent transit times and fuel consumption are calculated and used as input for a discrete-event simulation over the ships lifetime to assess the number of roundtrips, transported cargo and fuel consumption for the combination of different routes, dependent on the defined operational window. The gained results are used to calculate the costs per transported Twenty-foot equivalent unit (TEU) cargo between two ports and assess the sensitivity of this ship performance indicator to determine whether an economically advantageous transport system can be achieved. In addition, the effect of economy of scale using larger vessels can be evaluated.

However, the high degree of uncertainty in many of the input variables necessary for such a SBDS-tool remains a challenge. This applies especially to ice data predictions for arctic routes, which are of particular interest for this thesis. Furthermore, the influence of single variables on the final results is unknown. To address this complexity, a discrete-event simulation model was chosen as suitable method for the developed tool.

In order to show the applicability of the developed SBDS-tool, a comparative case study for three container vessels operating between Rotterdam (NL) and Yokohama (JP) is carried out. The results indicate that this SBDS-tool is capable of giving adequate support to ship operators and owners under the complex assumptions and uncertain inputs. In the specific case study, the NSR is not economically advantageous as compared to the SCR for the implemented ice data and assumptions made, but has the potential to become, under certain conditions, a valuable alternative in the future.

Kurzfassung

Die Russische Föderation möchte die Northern Sea Route (NSR) als eine Alternative zu der etablierten Suez Canal Route (SCR) aufbauen. Deswegen stehen Schiffseigner und Schiffsbetreiber vor der Herausforderung der Beurteilung, ob die NSR für sie ökonomisch vorteilhaft sein könnte. Um sie in dieser komplexen Aufgabe der Analyse der ökonomischen Machbarkeit der gemeinsamen Nutzung oben genannter Routen unterstützen zu können, stellt diese Diplomarbeit ein simulation-based decision-support (SBDS) - Tool, ein simulationsbasierendes entscheidungsunterstützendes Tool, vor. Das SBDS-Tool wird in zwei Schritten umgesetzt. Im ersten werden für schiffs- und routenspezifische Eisdaten die dementsprechenden Transitzeiten und der dazugehörige Treibstoffverbrauch berechnet. Dies wird dann als Input für eine diskrete Ereignissimulation über die gesamte Schiffslebenszeit verwendet, um die Anzahl der Roundtrips, die Menge der transportierten Fracht und den Treibstoffverbrauch für die Kombination der verschiedenen Routen analysieren zu können, das Ganze abhängig vom definierten Operational Window, sprich dem Zeitraum, in dem die arktische Route genutzt wird. Die so erhaltenen Ergebnisse werden benutzt, um die Kosten per transportierte Twenty-foot equivalent unit (TEU) Fracht zwischen zwei Häfen zu berechnen. Darauf aufbauend wird die Sensitivität dieser Leistungskennzahl (Key Performance Indicator) analysiert und überprüft, ob ein ökonomisch vorteilhaftes Transportsystem erreicht werden kann. Des Weiteren können mögliche Economy-of-Scale-Effekte untersucht werden.

Allerdings stellt die große Unsicherheit in vielen der Input-Variablen eine Herausforderung dar. Das trifft vor allem auf die Vorhersagen der Eisdaten auf den arktischen Routen, die für diese Diplomarbeit von speziellem Interesse sind, zu. Außerdem ist der Grad des Einflusses der einzelnen Variablen auf das Endergebnis, sprich die Kosten für die transportierte Fracht, unbekannt. Um dieser Komplexität Rechnung zu tragen, wurde eine Discrete-Event-Simulation als Ansatz für die Entwicklung des SBDS-Tools ausgewählt.

Um die Anwendbarkeit des entwickelten SBDS-Tools zu zeigen, wurde eine Case-Study für drei Containerschiffe, die zwischen den Häfen Rotterdam und Yokohama verkehren, durchgeführt. Die Ergebnisse zeigen, dass das SBDS-Tool auch unter

den komplexen Annahmen und der großen Unsicherheit der Input-Variablen fähig ist, eine angemessene Unterstützung für die Schiffseigner und Schiffsbetreiber bereitzustellen. Für die präsentierte Case-Study wurde herausgefunden, dass die NSR für die verwendeten Eisdaten und die getroffenen Annahmen nicht konkurrenzfähig gegenüber der SCR ist, aber das Potenzial hat, unter gewissen Bedingungen ökonomisch vorteilhaft zu werden.

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Nomenclature

NSR - Northern Sea Route

SCR - Suez Canal Route

TEU - Twenty-foot equivalent unit

NL – Netherlands

JP – Japan

SAR – Search and rescue

SBDS – Simulation-based decision-support

KPI – Key performance indicator

LNG - Liquefied Natural Gas

nm – nautical mile

1 Introduction

With the trend of diminishing sea ice in the Arctic and the political efforts of the Russian Federation the Northern Sea Route (NSR) becomes potentially more attractive for shipping companies and possibly a transport alternative to the current Suez Canal Route (SCR). Using the NSR, sometimes also referred to as “Arctic shortcut”, would reduce the travel distance between the ports of Europe and Eastern Asia up to 50 percent as compared to the traditional SCR. Hence, the NSR offers the potential of significant time and fuel savings. Furthermore, there is no risk of piracy along the route. However, there are various challenges related with operating in the high North such as the harsh environmental conditions, remoteness and the absence of adequate infrastructure for situations a vessel gets damaged and needs repair or for search and rescue (SAR). All in all, the decision whether ship operators are going to utilize the NSR depends whether the associated economic benefits are worth taking the related risks.

In order to assess the economic feasibility of the NSR, global developments that are setting the framework for this route need to be accounted for. Both, the possible demand for a new transportation route and future perspectives of the commercial shipping sector play a critical role in these considerations. Furthermore it has to be determined whether the global trend of rising temperatures and the melting of sea ice is going to continue and how this could affect the conditions along the NSR. In case these preconditions are favorable, the interests of the different stakeholders for operations along the NSR have to be analyzed.

Ship operators and owners are considered as the key stakeholders in this context. Their interest in the route is serving as a basis for the future integration of the NSR in the global seaborne transportation system. Therefore the aim of this thesis is to provide support for the decision making process of ship operators about a possible integration of the NSR in their business model. For them, several conditions such as the safety of the crew and vessel, the reliability of operations and maintaining a schedule must be met, but the real incentive for a potential use of the NSR is to reduce their costs of transporting cargo. The calculation of the cost per transported cargo unit is subject to many influences including the ice conditions over Russian legislation and the bunker price. All these influences have one thing in common; they are affected by a large uncertainty. Another challenge is the task of estimating the impact of this vast number of variables and the related uncertainty on the final result respectively cost per transported TEU. But even if the input variables are well known and of high accuracy, it remains very difficult to determine how each single variable affects the final result. In order to address this complexity it is expected that a simulation model is the right tool to give realistic results and to provide information on whether a robust transport system can be obtained.

1.1 Background to the transport system

The integration of a new route has an impact on the long-term strategy of a company and investment decisions have to match with this. Therefore the knowledge about which ship should be invested in or rented by long-term contract is essential for the success of a company. This is especially crucial for arctic routes since a ship with ice-class is heavier and primarily designed for ice-covered waters. Thus, these ships are less competitive when they are used on southern routes compared with vessels without ice class that are primarily designed for open water. All these decisions have a long-term impact on the strategic concept of a shipping company and, therefore, the present and future operation environment of the company need to be considered in great detail. Here, the term environment has a dual meaning: first the market environment that determines, depending on the world economy, the demand for transporting cargo, and secondly the natural environment that determines to what degree an arctic route can be utilized and which ship is expected to show the best performance under the expected conditions. A brief analysis of these two is presented in Sections 1.1.1 and 1.1.2. A stakeholder analysis of a shipping route applied on the NSR is described in Section 1.1.3.

1.1.1 Shipping industry and expected future trends

At the time of this study, the world economy is just recovering from the biggest economic crisis since the 1930s, which resulted in a strong negative GDP growth in 2008 and an ongoing influence of the global markets. Global seaborne trade is highly dependent on the global GDP and was therefore facing a decrease during this crisis as can be seen in Fig. 1. This strong relationship is bilateral as 85 percent of the global demand for transport is met by shipping (Det Norske Veritas 2013a). The currently reduced activity in trade led to an overcapacity in the global fleet. Nevertheless, the world economy is expected to grow in the next decades and so is expected world seaborne trade. The specific forecast for container seaborne trade is assuming an annually growth of just below six percent until 2020 as showed in Fig. 2. The container liner market is very close to the consumer and therefore influenced by future demographic developments. Especially in Asia, the population is growing significantly. For all these reasons, a growing demand for transportation of goods between Europa and Asia is expected. Therefore it seems that the basic prerequisite for an alternative sailing route like the NSR is given.

Today the main route for container shipping between Europe and Asia is going via the Suez Canal, making it one of the busiest shipping lanes worldwide. The Suez Canal is the bottleneck of the route and determines the maximum capacity. Currently, approximately 49 ships per 24 hours can use the canal (Cairo News.Net 2014). Although the Egyptian president Abdel Fattah al-Sisi announced plans to increase the capacity to 97 ships in the future, this still sets a limitation to the transport system (Cairo News.Net 2014). At the present state of a difficult economic situation, this is not really an important constraint though in the future with increased economic activity or even an economic boom it might be one. Therefore the NSR could not only be a possible alternative, but also serving as a supplement for the overcapacity.

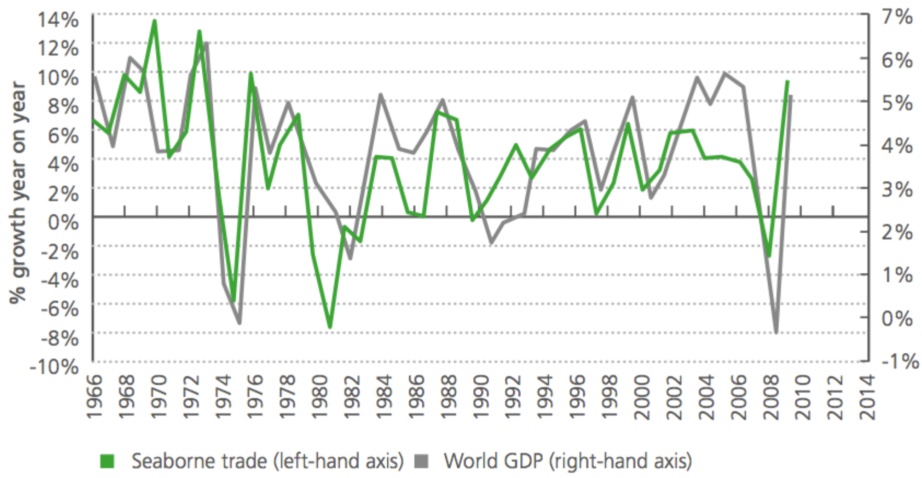


Fig. 1: Relationship between GDP growth and seaborne trade growth (Det Norske Veritas 2013a) (Det Norske Veritas 2013b)

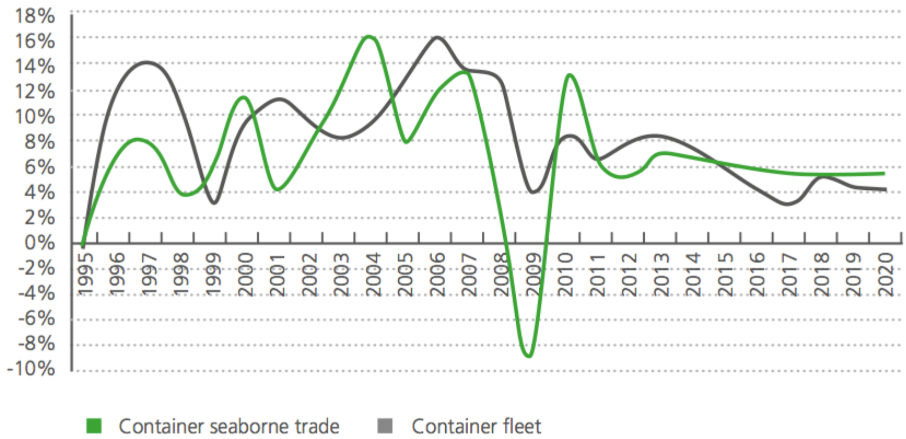


Fig. 2: Annual growth in the container fleet and container seaborne trade with included forecast (Det Norske Veritas 2013c)

1.1.2 Environmental conditions and climate forecast

The historic observations of the climate in the Arctic indicate that the temperatures in the region have been rising and the sea ice extent has been diminishing. Based on this, several climate models exist trying to predict the future sea ice cover. Although the prevailing predictions show a further reduction of sea ice in the future, at the same time, none of them expect that the sea ice cover will disappear completely during this century (Arctic Council 2006). Therefore the sea ice remains an important constraint for a ship's performance operating at the NSR in the future and has to be considered in the assessment of the economic feasibility.

In order to address this issue in more detail, Erikstad and Ehlers carried out a prediction of the future sea ice extent based on historic measurements to derive the predicted operational days along the NSR for different ice classes (Erikstad and Ehlers 2012). Fig.3 illustrates the mean sea ice anomaly measurements from 1980 to 2012 for the northern hemisphere. Each single measurement in the figure represents the average of summer and winter sea ice extent of one year. Although the standard deviation of the measurements is quite wide there is a clear trend visible indicating a decreasing sea ice extent. In Fig. 4 the predicted trend in operational days is presented. Therein, the operational days increase significantly until 2050. Then it will be even with a no-ice class vessel possible to utilize the NSR potential for 140 days per year. In addition, it can be seen in the figure that the higher the ice-class of a vessel, the longer the NSR can be used. A more detailed explanation of the different ice classes will follow later. Less ice means in general that the ship can go faster, which would lead to shorter transit times. As an alternative the ship could go with the same speed but less power is needed, which would make additional fuel savings possible. Furthermore, the easier navigation, less need for icebreaker support and less investment costs for building vessels ice-classed are all reasons for an expected higher economic feasibility of the NSR if the trend in diminishing sea ice is continuing.

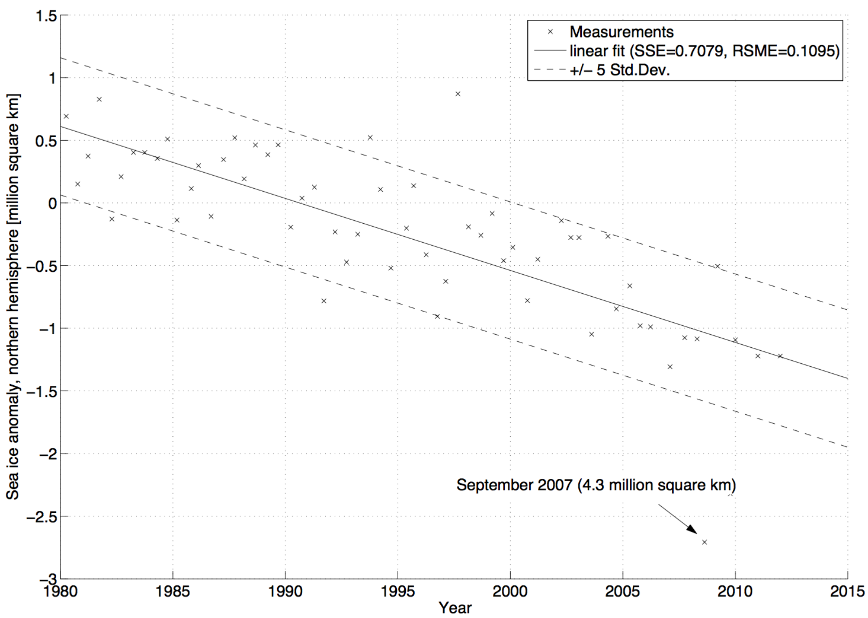


Fig. 3: Mean sea ice anomaly measurements and trend for the northern hemisphere (Erikstad and Ehlers 2012)

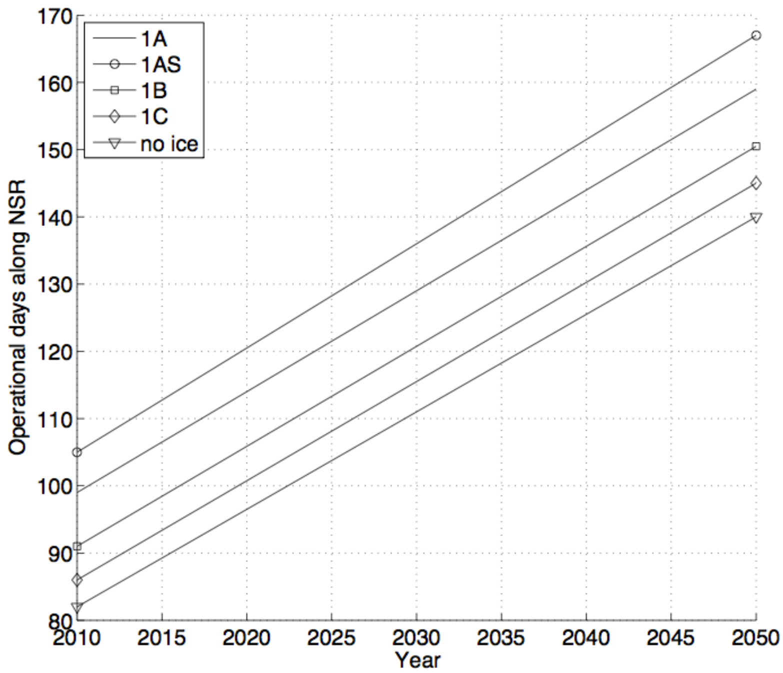


Fig. 4: Current and predicted operational days along the NSR for different ice classes (Erikstad and Ehlers 2012)

1.1.3 Stakeholders

A shipping route is subject of interest for groups affected in one or another way by it, the so-called stakeholders. For them, the success of the route is represented by a Key Performance Indicator (KPI) that reflects their interest. For the vessel and cargo owner this is first of all the profitability of the route. If a route is considered as not profitable for them, it will simply not be used and it is not necessary to analyze the other KPI's further. This KPI is serving as a basis for the analysis of the other ones. Therefore the focus of this thesis is on the profitability respectively feasibility of integrating a route in a transport system. This is applied on the example of the NSR.

The detailed list of KPI's and the corresponding stakeholder is shown in Table 1. It can be seen that the vessel and the cargo owner have matching interests. Besides the profitability, the safety of the crew and the vessel are of interest. This includes the structural integrity of the vessel hull, which is indispensable under arctic conditions, but also the operational integrity of propulsion and other systems like auxiliary engines. Furthermore, the safety and reliability of operations as well as the maintenance of a schedule are essential requirements for the successful integration of a shipping route. This is particularly true for liner shipping. In case of occurring delays this could weaken the reputation and, thus, the competitiveness of a company. The need for an adequate SAR infrastructure is also a KPI for the insurance companies. In case this requirement is fulfilled well this could result in lower insurance premiums. The NSR administration office is interested that all the requirements of the sailing permit are fulfilled according to the Russian law (The Northern Sea Route Administration 2014). The company operating the nuclear icebreakers along the route, called Rosatomflot, is interested in maximizing, depending on the possible capacity, the number of vessels that use the icebreaker assistance. With a higher number of vessels the high costs of running can be paid off more quickly. The regulatory body acts, besides the interest that the standards are fulfilled, according to the KPI that the operational safety is high. This is the same as for the insurance companies and shows that one KPI can be the same for different stakeholder. On the other hand, the interests may differ greatly from each other. This could be the case for the KPI of minimizing the pollution of the local population and the KPI profitability of the vessel owner. The lower the quality and therefore also the price of the used bunker oil is, the higher is the profitability for the vessel owner, but it has more pollutants. However this conflict of interest can be solved by environmental legislation, which asks for higher route fees for higher polluting vessels. In this way there is an incentive for the vessel owner to reduce his pollution and the local population is profiting at the same time. Nevertheless, such a conflict of interest can occur not only between different stakeholders, but also for the same stakeholder. For example is the KPI of maximizing the benefits of the use of the NSR in terms of increased employment of the local population and industrial development higher with more traffic along the NSR. Since this might be again linked with a higher pollution it could be contrary to the KPI of minimizing the pollution. The stakeholder shaping the framework of the NSR is Russian politics. They are making the decisions for future SAR infrastructure, the legislation and also control Rosatomflot. Their interest is to foster the NSR as an alternative to the SCR and consequently to increase the traffic along the route. Above all might also the geopolitical ambitions of the Russian Federation towards expanding their influence in the Arctic play a role.

Table 1: Stakeholder and Key Performance Indicators for the NSR, adopted from (Milaković 2014)

Stakeholder	KPI
Vessel & cargo owner	- Profitability - Safety of crew - Structural integrity of vessel hull - Operational and structural integrity of machinery, propulsion and other systems - Reliability of operations & maintaining a schedule - Assurance of infrastructural and SAR support by ice breakers fleet and local SAR centers
NSR administration office	- Fulfillment of requirements stated in sailing permit
Rosatomflot	- Usage of icebreaking assistance by as many vessels sailing NSR
Regulatory body (IMO, Flag State, Classification Society)	- Fulfillment of standards and operational safety
Insurance companies	- Safety of operations - Assurance of infrastructural and SAR support by ice breakers fleet and local SAR centers
Local population & environment	- Minimization of pollution - Maximization of benefits (increased employment of local population, industrial development)
Russian Federation politics	- Increase of NSR traffic and making it an important sailing route

In the first part of this chapter the background of the transport system was discussed. First, studies about the future market situation of the shipping sector were analyzed. The conclusion from this analysis is that the seaborne trade in general and in particular for container shipping is expected to grow until 2020. This means a favorable market environment for the utilization of a new shipping route. Secondly, the trend of rising temperatures and diminishing sea ice in the Arctic and their possible influences on the ships performance were studied. In case this trend should be continued it is expected that this has a positive influence on the ships performance in arctic waters. Thirdly, the stakeholders and the KPIs of the NSR were identified and discussed. It was found that the profitability is servings as a basis for further analysis of the other KPIs. Therefore one objective of this thesis is that the developed SBDS-tool is able to compare the profitability of different route options including the NSR and the SCR. In the following part the definition, historic background and current use of these two route options are analyzed to give a better insight.

1.2 Northern Sea Route

1.2.1 Definition

The NSR is a series of shipping lanes from the Atlantic Ocean to the Pacific Ocean along the Russian coast crossing five Arctic Seas: the Barents Sea, the Kara Sea, the Laptev Sea, the East Siberian Sea and the Chukchi Sea.

According to the legislation of the Russian Federation, the whole water area adjacent to the Northern coast of Russia including the internal seawaters, the territorial sea, the adjacent zone and the exclusive economic zone confined with the Bering Strait in the East and Novaya Zemlya in the West is belonging to the NSR waters (Northern Sea Route Information Office 2014). The actual length of the route depends from voyage to voyage on the ice conditions and which legs are chosen for the route. It varies approximately between 2100 and 3400 nautical miles (Drent 1993).

1.2.2 Vessel restrictions

In order to get a sailing permit for the NSR, a vessel has to fulfill certain requirements. One of them is concerned with the dimensions of the vessel. There are several parts of the route running through shallow water and therefore the current draft limitation is set to 15 m taking into consideration the latest sounding works in 2013 (Melenas 2013). The breadth limitation is depending on the type of icebreaker support. The presently used nuclear icebreakers have a beam of 30 m and create a brash ice channel of approximately the same size. Therefore one icebreaker can assist a vessel with up 30 m breadth. From 2017, a new generation of nuclear icebreakers will start operations, setting a new breadth limitation to 34 m (Barentsobserver 2013). However, it is already possible to assist accordingly bigger vessels with the use of two nuclear icebreakers, thereby bypassing this limitation. The second important restriction of the NSR is the required ice-class in order to get a sailing permit for the

NSR. The basic requirements for an ice-class vessel is that the ship's hull is strengthened to resist the higher pressure acting against it due to the ice and a significant higher propulsion power to overcome the additional ice resistance. The detailed requirements are set by different classification societies like the Finnish Transport Safety Agency and the Swedish Maritime Administration for the Finnish-Swedish Ice Class Rules (FSICR). The ice-class rules applied on the NSR are set by the Russian Maritime Register of Shipping (RMRS) and serve as an entry requirement for the NSR. Depending on the ice-class of the ship it is allowed to use the NSR independently, with icebreaker assistance or the access can be refused. The detailed rules and requirements can be found at the official website of NSR Administration: www.nsra.ru.

1.2.3 Historical background and current use

Initially, economic considerations acted as the main driver for exploring the NSR. In the 16th century, the European colonial powers were expanding their empires and, in this process, they were also searching for an alternative seaway to Asia. The shorter a route the more profitable it would be. So Great Britain and the Netherlands sent out expeditions to the Russian Arctic to find the so-called Northeast Passage (Ragner 2008). They managed to map a large area of the western part, but failed to sail the whole route due to the difficult sailing conditions. It took until 1879 as Finnish-Swedish Arctic explorers managed to successfully sail the whole NSR. It has to be mentioned that already 200 years earlier the Russians mapped the Arctic shores in the north to extend their sovereignty (Ragner 2008).

In 1917 the Russian Revolution took place and the access to the NSR was restricted for foreign vessels. Therefore the possibility of developing the NSR as important international waterway disappeared. In the 1930s the Soviets started to develop the NSR as a national transportation route to support the exploration of natural resources in the north (Ragner 2008). In addition, it enabled the establishment of civil, scientific and military settlements in the Arctic and became in general an important part of cold war strategies of the Soviets. Activity along the NSR rose gradually until 1987 when it reached its peak (Ragner 2008). After this point, the economically struggling Soviet Union could not keep the high subsidies up. At this time, president Mikhail Gorbachev proposed to open up the NSR for foreign vessels. From this point, it took four more years until the official opening on 1. July 1991. Beside the fact that the opening was part of his new policy of opening the Soviet Union in general, there was also the strong interest to get more hard currency in the budget since vessels would have to pay for icebreaker support and infrastructure (Ragner 2008). However these hopes didn't come true as statistics for the transported cargo show. In **Fig. 5** a strong decline in the transported cargo from approximately 6500 thousand tons in 1987 to around 1500 in year 2000 is illustrated. After stabilizing at this low level it slowly increased again in the year 2009. At the same time the two German vessels of the Beluga group claimed the first commercial transit of foreign vessels. Nevertheless the first foreign vessel was a Finnish tanker Uikku in 1997 (The New York Times 2009). This shows that the NSR remained, also after the opening, mainly unused by foreign ships. Although this is changing slowly the majority of ships still remain Russian as shown in **Fig. 6**. This can be explained by the primary purpose as an internal waterway for the supply of the Siberian settlements and industry in the north. Furthermore the growing exploitation of Russian natural resources will be an additional driver for further traffic increase.

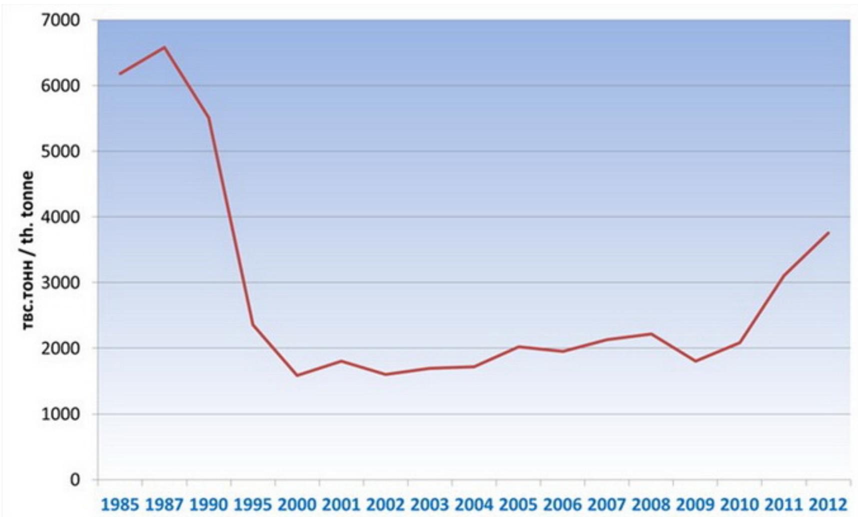


Fig. 5: Transported cargo along the NSR from 1985 to 2012 (Northern Sea Route Information Office 2012)

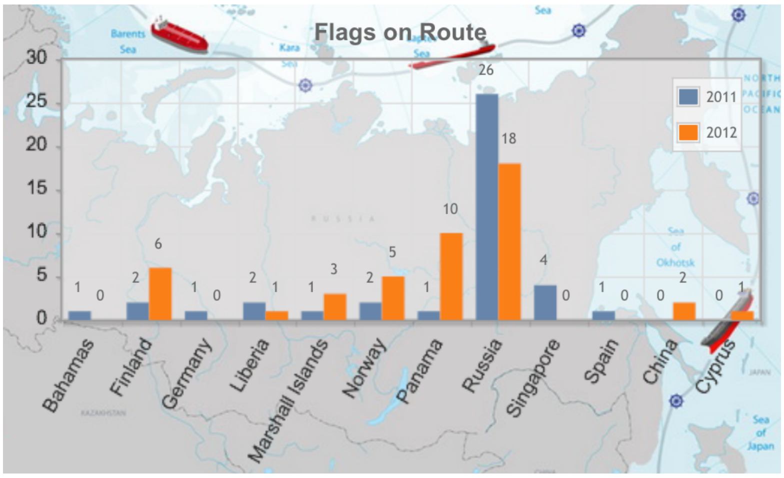


Fig. 6: Flags on route for NSR (Northern Sea Route Information Office 2012)

1.2.4 Future perspective

The president of the Russian Federation stated at the Arctic Forum Arkhangelsk in 2011: "I want to stress the importance of the Northern Sea Route as an international transport artery that will rival traditional trade lanes in service fees, security and quality," (Bryanski 2011). In his speech he highlighted also the Russian commitment to support this development. This seems also necessary since the infrastructure along the NSR has some potential for improvement. Especially the SAR facilities are not appropriate to support a vessel in an emergency situation in a reasonable time. Nevertheless, there are efforts to establish new SAR centers and to bring the infrastructure up to date. Furthermore, new nuclear icebreakers and conventional icebreakers have been ordered by the Russian Federation respectively its state-owned companies (Barentsobserver 2013). This should make it possible to support an increasing traffic volume along the NSR and in addition improve the SAR capabilities.

1.3 Suez Canal Route

1.3.1 Definition

In this master thesis the SCR is defined as the route connecting Rotterdam in Europe and Yokohama in Eastern Asia along the Atlantic, Mediterranean Sea, the Suez Canal, Red Sea, Gulf of Aden, Arabian Sea, Indian Ocean, Malacca Strait, Singapore Strait, South China Sea and East China Sea. The main constraint and bottleneck of this route is the Suez Canal because of its limited capacity and its single lane design.

The Suez Canal is a waterway in Egypt between the port cities Port Said and Port Taufiq at the city of Suez connecting the Mediterranean Sea and the Red Sea. This artificial canal is, including the northern and southern access channel, 193.30 km long and is lying at sea level (Suez Canal Authority 2 2014). Therefore, watergates are not required in contrast to the Panama Canal, which has to overcome a difference in altitude. According to the Convention of Constantinople, the Suez Canal is open to all vessels, commercial and warships, of all nations without discrimination, in peace and in wartimes (Suez Canal Authority 2014).

1.3.2 Vessel restrictions

The Suez Canal is setting the restrictions for the vessel dimensions along the SCR. The maximum dimensions are currently set with 20.1 m draft and a beam width of 50 m. With this dimensions it is able to serve most vessels. Currently the whole global fleet of container ships fit through the canal (Suez Canal Authority 3 2014).

1.3.3 Historical background and current use

The first canal in Egypt was already built in 1874 B.C. during the regency of the pharaohs (Suez Canal Authority 2014). However, due to problems caused by silting the canal was abandoned. After this it was closed and reopened several times. Nevertheless, this was still not comparable with what we know today as the Suez Canal. The first attempts for a modern canal came from the Egypt Expedition of Napoleon Bonaparte, who had the idea that this would disturb the British trade with India (Suez Canal Authority 2014). The project was started, but then stopped because of a miscalculation of Napoleon’s engineers, who believed that the sea level of the Red Sea was around ten meters higher than that of the Mediterranean Sea. They had the fear that the digging of a canal would lead to flooding of the Nile Delta and that the Red Sea would flux into the Mediterranean Sea (Suez Canal Authority 2014).

In 1854 the French diplomat and engineer Ferdinand de Lesseps could convince the Egyptian viceroy of the project. Four years later the La Compagnie Universelle du Canal Maritime de Suez (Universal Company of the Maritime Suez Canal) was founded with the authority to dig the canal and operate it for 99 years (Suez Canal Authority 2014). It was agreed that, after this period, the canal would return to the Egyptian government. In 1859 the construction work started and lasted for ten years. The British and Turkish made several diplomatic attempts to shut down the work, which led to delays, but could thanks to the intervention of Napoleon III not stop the project. Finally, on 17th November 1969 the Canal was officially opened (Suez Canal Authority 2014).

In 1875 the British government bought the shares owned by Egyptian interests. In 1888 the above-mentioned Convention of Constantinople was signed. As the British wanted to secure their colonial interests the Anglo-Egyptian Treaty was signed in 1936 (Suez Canal Authority 2014). It allowed Britain to have a defensive force along the Suez Canal one. The British control over the canal remained also during the Second World War until 1956 when the Egyptian president Gamal Abdel Nasser nationalized the Suez Canal. This led to the so-called “Suez-Crisis”. The answer of the west to Nasser’s move was a British-French-Israeli invasion of Egypt that also resulted in the closing of the Canal until 1957. The canal was closed a second time during the “Six-Day War” between Arab States and Israel in 1967. It took until 1975 for the canal to open again, as a consequence of a disengagement accord between Egypt and Israel (Suez Canal Authority 2014).

Since then, the canal has been open and was expanded several times until todays dimensions of 24 meters depth and 205 meters wideness (Suez Canal Authority 2 2014).

1.3.4 Future perspective

The Suez Canal is one of the busiest shipping lanes worldwide and therefore there is an interest to increase its capacity. In particular for Egypt the Suez Canal is vital for the economy and an important source of foreign currency, especially now in a period of political instability. On 5th August 2014 Egypt's president Abdel Fatah al-Sisi announced the construction of a new 45-mile lane. This would enable ships to travel in both directions in the otherwise single lined canal for approximately half of the canal's length (The Guardian 2014).

In the second part of this chapter two shipping routes, namely the NSR and the SCR, were presented. The historic and current use of them was discussed. It could be seen that the SCR is serving as the main shipping lane for trade between Europe and Asia. This is especially true for container shipping. The traffic volume along the NSR reached its peak at the end of the Soviet Union. With the breakdown of the Soviet Union the amount of transported cargo decreased dramatically and is slowly increasing again since around 2009/2010. Furthermore, the vessel restrictions of the different routes were discussed. The NSR is more restrictive in terms of the dimension of vessel types, but also in terms of the design as compared with the SCR. In addition the different plans for making the routes more attractive have been mentioned. In the following chapter a look is taken at the state of the art studies related to arctic shipping in general and in particular for the NSR and SCR.

2 State of the Art Analysis

There have been previous studies published about different aspects of the NSR. The probably most holistic study was the International Northern Sea Route Program (INSROP) from 1993 until 1999. The total number of 167 reports dealt with the natural, social, economic, legal and political environment to name the most important. Although this study provides a very good knowledge base, it does not support the individual ship operator in his question whether the NSR could be useful in its individual case. Furthermore the data is not up to date. Especially the ice conditions changed significantly since the INSROP was completed.

Verny et al. (Verny et al. 2009) analyzed the economic aspects of the NSR and were looking into detail at the cost perspective for transporting cargo along the NSR. However this was not done by the use of a simulation model. Therefore the route specific ice conditions and the influence on the transit times were not included.

Erikstad and Ehlers developed a decision-support model that is identifying the most feasible ice class for a liner vessel operating along the NSR (Erikstad and Ehlers 2012). Although their paper is predicting the ice conditions based on past developments and showing the influence on the operational days along the NSR the model requires the transit times as an input parameter and doesn't calculate it in the model. Therefore it is not possible for a ship operator to decide solely based on the route-specific ice conditions and the vessel parameters if this is a feasible solution for him. In order to do so first the ships performance in ice would have to be calculated. Despite the fact that the presented paper is including risk and reliability in its considerations, it is not possible to check whether a robust transport system is provided (Erikstad and Ehlers 2012).

Erceg and Ehlers presented a paper on a transit simulation model that is capable of assessing different performance indicators for ships operating in ice-covered waters (Erceg and Ehlers 2014). These include the transit times a ship needs under specific ice conditions. Based on this, the number of transits a ship can achieve in a certain time period can be obtained. In addition, the sensitivity and robustness of the transport system is assessed. A comparative case study was carried out for four different ice classes for an ice-capable ship operating between the ports of

Rotterdam and Sabetta. Hence the focus of this paper is on the performance of the ship in ice more in a technical sense and the assessment of the economic consequences of the obtained results is missing in order to have a holistic view on the transport system.

Tõns et. al developed a concept for an ice condition database, which serves as a basis for the determination of route specific ice conditions (Tõns 2014). Its aim is to ensure safe vessel transits. In addition the database could be used as input for the calculation of transit times depending on the route-specific ice conditions.

Liu and Kronbak (Liu and Jacob 2010) were assessing the economic viability of the NSR as compared with the SCR between Rotterdam and Yokohama. The focus of this study is on the economic perspective that the NSR offers as compared with the SCR. However the speeds along the NSR were assumed on an average basis, obtained from a paper of Wergeland (Wergeland 1992), which makes it difficult to estimate how the results would change for different ice conditions along the route or the use of another vessel type.

Bock und Polach et al. extended the ship merit factor (SMF) application for ice going vessels to identify the best economical design (von Bock und Polach et al. 2012). In the most recent paper it was completed by a comparative approach resulting in the introduction of the comparative ship merit factor (CSMF) that also includes the productivity as parameter. In the case study the design approach was applied to compare different oil tankers and conclude if it is advantageous that the ship is ice-classed and also which ice class is favorable (von Bock und Polach et al. 2014). Nevertheless this was not applied on container shipping.

Bergström et al. were applying a discrete event simulation tool for an approach towards mission-based design of an arctic maritime transport system. The approach implements route specific ice and stochastic conditions like weather. A case study for Liquefied Natural Gas (LNG) transport between Narvik and Sabetta was carried out. The ice-vessel interaction in the model is limited to ice resistance (Bergström 2014).

Omre was identifying an assessment framework for the integration of NSR and SCR in an economically feasible transport system (Omre 2012). Nevertheless, the simulation model that was developed for this purpose seems more or less specifically designed for the use of the NSR and SCR, which could be a problem for comparing other routes. Furthermore, it is not possible to implement routes with the latitude/longitude coordinates and the corresponding ice conditions at these waypoints.

Sørstrand was looking into the assessment of design aspects for vessels using NSR in addition to SCR (Sørstrand 2012). Furthermore, a decision support model for the evaluation of the potential financial benefit was presented. But again, it is not possible to implement routes just by its waypoints and the prevailing ice conditions there.

Det Norske Veritas (DNV) developed a tool for the simulation of ship performance and economic aspects for Arctic shipping. It serves as a decision support tool to assess strategic options and incorporates models for ship performance in ice and open water. The travel time, fuel consumption, emissions and overall economics are the main output. It is possible to simulate entire transits through the Arctic, but in the case study this was only applied for tankers and again not for container shipping (Det Norske Veritas DNV 2013).

In the book “The Arctic in World Affairs: A North Pacific Dialogue on the Future of the Arctic “ edited by Young et al., different aspects for arctic maritime shipping and logistics in the high north are discussed (Young, Deog Kim and Kim 2013). These include the present state of infrastructure along the NSR and the conditions under which the NSR could be economical feasible.

Østreng et al. were writing in their book “Shipping in Arctic Waters - A comparison of the Northeast, Northwest and Trans Polar Passages” (Østreng, et al. 2012) about the different available transport corridors. Furthermore, the geopolitics and power constellations in the Arctic, resources, economic trends, environmental challenges, shipping and arctic infrastructure were analyzed.

The above-mentioned studies address various aspects of the NSR, which altogether form a good knowledge base for the transport system. Nevertheless, for ship operators it is difficult to filter out and examine the information relevant for the individual company. For them it is crucial to know whether it is economic feasible to utilize the NSR with a specific vessel under certain ice conditions. In addition the optimal degree of integrating the NSR in the existing transport system that is currently used by the company has to be discussed. In other words, the heavy ice conditions prevailing partly in the year could make it advantageous to use the NSR only in the low-ice season and use the SCR the rest of the year. The question is for what period of the year the different routes should be used or combined. At the moment there is a gap in the state of the art studies for providing support to the ship operator in the decision-making whether the NSR is viable in its individual case. In order to fill this gap a tool has to be developed where the ship operator can enter the expected route waypoints, route-specific ice conditions and vessel details in order to get as result the costs of transporting cargo between the selected ports. This issue is, especially for the application of container shipping, absent in present literature. Furthermore, it should be tested if the tool that is to be developed should be simulation-based since this could be advantageous for a high number of input variables with high uncertainty like in the case of the NSR. This method was applied in related applications for logistic purposes. After analyzing the state of the art literature it can be said that such a SBDS-tool was not developed yet for the application of examining the economic feasibility of the NSR and SCR. In addition, the model should be capable of discussing possible economy of scale effects, for the different ships available for operation at these routes, since this issue is also missing in the present studies.

In this chapter an overview of the state of the art literature was given. Furthermore, a gap in present studies for a SBDS-tool was identified, which should be filled by this master thesis. In order to reach this goal, methods for the ships performance in open water, ice and also in economic terms have to be introduced. This is done in the following chapter.

3 Methods

To assess the economic feasibility of the NSR, it is essential to know the fuel consumption and the transit time. Both are directly dependent on the ship performance in open water and in ice. In order to obtain this, it is necessary to calculate the open water and ice resistance for a specific ship design first. In this chapter the theory and the required methods are explained.

3.1 Performance of ships in open water

There are different approaches for the calculation of the open water resistance of ships. The best known is probably the method of Holtrop-Mennen. It is used widely and has the advantage of being very flexible. On the other side it requires many details as input for the calculation, which could be unfavorable when only the basic dimensions of a ship are known or when the calculation procedure needs to be quick (Kristensen and Lützen 2012). Another method is the one of Hollenbach who analyzed many model tank tests to get a higher reliability of the performance prognosis of modern cargo ships (Bertram and Schneekluth 1998). In this thesis the calculation procedure from the report of Kristensen from Technical University Denmark and Lützen from University of Southern Denmark (Kristensen and Lützen 2012) is followed. They base their calculations on the original resistance calculation method developed by Guldhammer and Harvald (Harvald 1983). It depends on relatively few parameters, which has the advantage that different ship designs can be easily implemented in the model. In the following the particular steps of the calculations are illustrated.

The desired result of the resistance calculation is the total resistance R_T for different speeds, to fit in the next step a curve through them. This makes the SBDS-tool capable of accepting every input speed between 0 and the maximum vessel speed. The input parameters for the calculation are the main vessel dimensions as the length overall L_{OA}, draught T, beam B and two coefficients for the hull form of the ship, the block coefficient C_B and the midship coefficient C_M. Based on these values the wetted surface and the total resistance coefficient of the ship can be calculated. The wetted surface is the surface of the vessel that is in contact with water and therefore from particular interest for the resistance. The total resistance coefficient is consisting of several sub-factors that are considering the roughness of the hull, the air resistance that is caused by movement of the ship through air, wave resistance, viscous pressure resistance and additional resistance due to hull form. Furthermore, a correction coefficient is included for the differences of the small-scale ship model, on which the method is based on and the real size ships. In the final step, the following speed-dependent equation has been used to calculate the total resistance R_T in open water

$$R_T = \frac{1}{2} \cdot C_T \cdot \rho \cdot S \cdot V^2, \tag{1}$$

where C_T is the total resistance coefficient, ρ is the mass density of water, S is the wetted surface of the ships hull and V is the sailing speed. After R_T has been calculated for several different speeds, the Matlab Curve Fitting Tool has been used to fit a curve through the obtained resistance points. As an example, the fitted open water resistance curve for the CV 4400 ICE vessel is shown in the figure below.

3.2 Performance of ships in ice

The performance of ships in ice is mainly limited by the ice conditions. Although the ship experiences also open water resistance, the ice resistance is the dominating influence. Therefore the minimum speed for a given ice thickness is normally defined as a requirement in vessel building contracts. In the Finnish-Swedish ice class rules this so-called basic rule requirement is at least 5 knots speed in channels of a given thickness (Riska and Juva 2002). However, there are various ice features that influence the speed and performance of a vessel in ice such as ice thickness, ridges and compression. In calculations for ice resistance, there are mainly two types of ice considered, level ice and brash ice. According to the definition level ice is sea ice, which has not been affected by deformation. That means that vessels, which navigate independently in ice such as icebreakers, experience this type of ice. Vessels following an icebreaker experience brash ice, which is the broken level ice. In this channel created by an icebreaker it is much easier to navigate and the vessel needs less power because of the reduced resistance compared with level ice. The established method to measure the performance of a vessel in ice is the ice thickness-velocity curve (h-v curve). It shows what speed a vessel can reach at a given ice thickness and is used in this thesis for the prediction of the vessel speed along the NSR. To get the h-v curve the ice resistance for different ice thicknesses and the net thrust available to overcome the resistance have to be calculated (Omre 2012). A ship operating in ice is facing two kinds of resistance, the open water resistance R_{ow} and the ice resistance R_{ICE}. Since both are acting on the ship at the same time they can be super-positioned as showed in following equation:

$$R_{Total} = R_{OW} + R_{ICE} \tag{2}$$

However, the open water resistance is neglected for the generation of the h-v curve, because ships operating in ice are going in general at a quite low speed and the fraction of the open water resistance of the total resistance is small. Another assumption of this thesis is that ships operating in ice have always icebreaker support and follow them in the created brash ice channel. The breaking of the brash ice and displacing in down- and sideways and the friction along the parallel midbody form the brash ice resistance ships have to overcome in order to move forwards (Riska and Juva 2002). The calculation method will be explained in the following section

3.2.1 Channel resistance in brash ice

The brash ice resistance R_{ch} was calculated by the speed-dependent equation from Juva and Riska (Riska and Juva 2002).

$$R_{ch} = \frac{1}{2} \cdot \mu_B \cdot \rho_\Delta \cdot g \cdot H_F^2 \cdot K_P \cdot \left[\frac{1}{2} + \frac{H_M}{2 \cdot H_F}\right]^2 \cdot \left[B + 2 \cdot H_F \cdot \left(\cos\delta - \frac{1}{\tan\psi}\right)\right] \cdot (\mu_h \cdot \cos\phi + \sin\psi \cdot \sin\alpha) + \mu_B \cdot \rho_\Delta \cdot g \cdot K_0 \cdot \mu_h \cdot L_{par} \cdot H_F^2 + \rho_\Delta \cdot g \cdot \left[\frac{L \cdot T}{B^2}\right] \cdot H_M \cdot A_{WF} \cdot \mathrm{Fn}^2 \tag{3}$$

where $\mu_B = 1 - p = 0.8,\ \rho_\Delta = 150\ \left[\frac{kg}{m^3}\right],\ K_P = 6.5,\ K_0 = 0.68,\ \mu_h = 0.02$

p is the porosity and μ_B therefore can be called the porosity factor, $\rho_\Delta$the difference between the densities of water and ice, g represents the gravity constant, μ_h the corresponding coefficient of friction between the ice and the hull, A_{WF} the waterline area of the foreship and Fn the Froude number. K_P is constant and stands for the passive stress, and K_0 is the coefficient of lateral stress at rest (Riska and Juva 2002). The values for both constants have been found in the book "Performance of Ice-strengthened Ships in the Northern Baltic Sea in Winter 1991" (Kujala and Sundell 1992).

A typical brash ice channel after an icebreaker broke the level ice is shown in Fig. 7. The brash ice thickness in the middle of the channel is represented by H_M. The ice is broken and displaced by the bow of the ship and then partly shifted to the side against the parallel midbody of the vessel. The ice thickness there is represented by H_F and can be calculated using following equation:

$$H_F = H_M + \frac{B}{2} \cdot \tan\gamma + (\tan\gamma + \tan\delta) \cdot \sqrt{\frac{B \cdot \left[H_M + \frac{B}{4} \cdot \tan\gamma\right]}{\tan\gamma + \tan\delta}} \tag{4}$$

If the conditions ship beam $B > 10\,m$ and $H_M > 0.4\,m$ are fulfilled, a simplified equation can be applied:

$$H_F = 0.26 + (B \cdot H_M)^{0.5} \tag{5}$$

The previously mentioned accumulation of brash ice on the side of the channel is causing there a significantly higher total ice thickness than the previous unbroken level ice. This large area of friction between the vessel and the ship's hull is shown in Fig. 8. The slope angles γ and δ have the values 2° and 22.6° respectively (Riska and Juva 2002). The flare angle ψ in the equations can be calculated using following equation:

$$\psi = \tan^{-1}\left[\frac{\tan\phi}{\sin\alpha}\right] \tag{6}$$

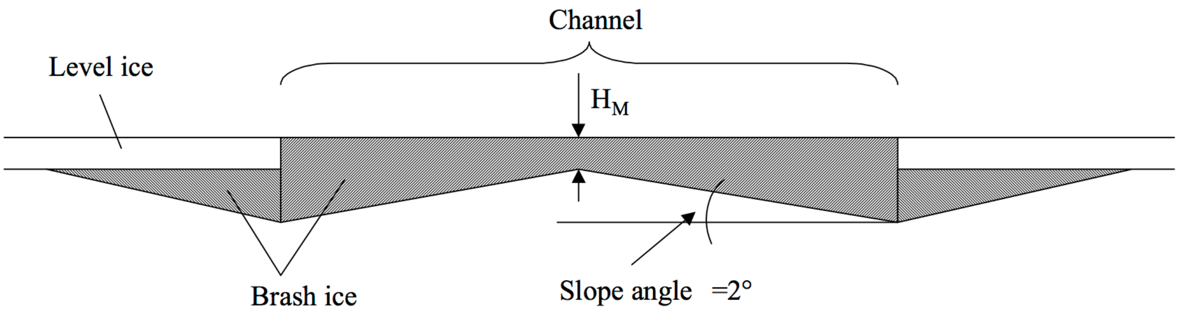


Fig. 7: Brash ice channel (Riska and Juva 2002)

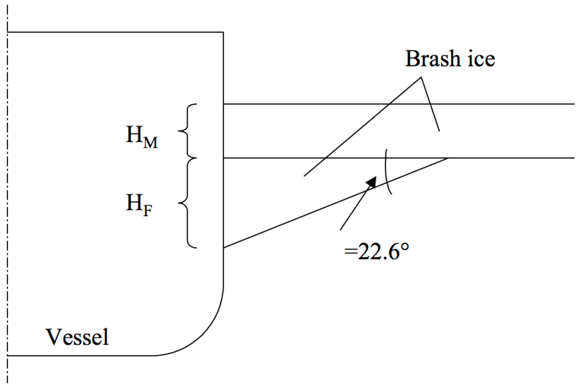


Fig. 8: Sectional view of vessel in brash ice channel (Riska and Juva 2002)

3.2.2 The net thrust concept

The net thrust T_{net} is the thrust available to overcome the ice resistance after the thrust needed to overcome the open water resistance R_{ow} is considered (Riska and Juva 2002). It can be calculated with the following equation:

$$T_{net}(v) = T_{tot}(v) \cdot (1 - t) - R_{ow}(v) \tag{7}$$

where $T_{tot}(v)$ is the total available thrust, v is the speed and t is the thrust deduction fraction. The speed dependency of the equation is taken by the quadratic factor f(v) into account. In practice that means that when the ship speed is zero, the net thrust is equal to bollard pull. On the other hand the net thrust is zero when the ship is operating at maximum open water speed. At this point the engine is operating at maximum power and therefore there is no power left for additional ice resistance. Consequently the net thrust is zero in this case.

$$T_{net}(v) = f(v) \cdot T_{pull} = \left(1 - \frac{1}{3} \cdot \frac{v}{v_{ow}} - \frac{2}{3} \cdot \left(\frac{v}{v_{ow}}\right)^2\right) \cdot T_{pull} \quad (8)$$

where T_{pull} is the bollard pull, v the speed and v_{ow} the maximum open water speed.

3.2.3 H-v curve

In order to obtain the h-v curve several resistance curves have to be generated and intersect with the T_{net} thrust curve. The points of intersection serve as basis for the h-v curve.

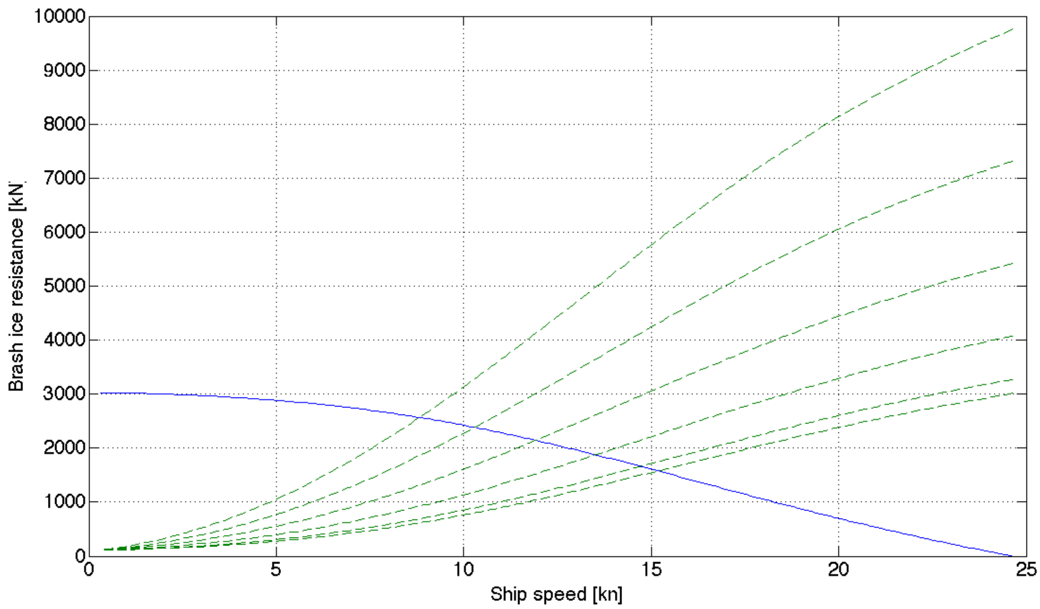


Fig. 9: Net thrust concept

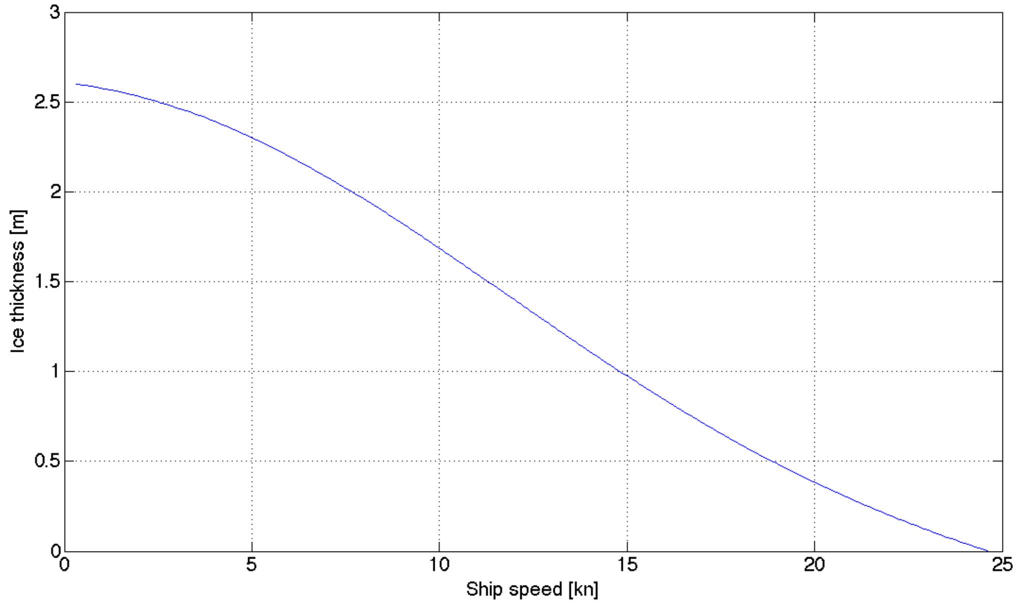


Fig. 10: H-v curve

3.3 Performance in economic terms

The assessment of the economic performance of a shipping route is essential for stakeholders to take investment decisions or decide which route is worth to operate. Nevertheless, the interests can vary from stakeholder to stakeholder. In this thesis the observed perspective is the one of a ship operator, who is renting ships on long-term agreements and wants to know which possible route-vessel-combination is most beneficial. The total costs for the operation of a vessel on specific route(s) is assumed in following simplified equation:

$$Total\ costs = charter\ costs + fuel\ costs + route\ fees + insurance\ costs \qquad (9)$$

In this equation the fixed costs for the headquarter, onshore personal, etc. are neglected since these are assumed to be the same regardless on what route which type of vessel is operated on. In addition, the route comparisons are carried out for the same destination ports, what results in the same port and cargo handling costs. Therefore, these are not considered in the following calculations as well. As simple and appropriate scale for comparing the different routes, the costs per transported TEU have been chosen. The detailed equation is:

$$\frac{Costs}{transported\ TEU} = Time\ charter\ rate \cdot Simulation\ time + Fuel\ consumption \cdot Bunker\ price + Suez\ canal\ fee \cdot Suez\ transits + NSR\ icebreaker\ fee \cdot NSR\ transits + Insurance\ costs\ Suez + Insurance\ costs\ NSR \tag{10}$$

This equation is meant as a basic first evaluation of different route options and further more detailed calculations have to be carried out to validate the obtained results. However, the task of this thesis is to develop a SBDS-tool and not to evaluate the output of the simulation until the last accuracy.

In this chapter, the performance of ships in open water and ice were discussed. In addition, the relevant costs were introduced as basis for assessing the performance in economic terms. Based on these methods, the SBDS-tool was developed, which is introduced in the following chapter.

4 Simulation-based decision-support tool

The main objective of the tool presented in this thesis is to serve as a SBDS-tool for ship operators to evaluate the economic feasibility of different route options. The model is able to compare routes that are operated on a year round basis, but also combined routes. Such routes make use of a seasonal time window to operate on a second route when the conditions are beneficial there in addition to the “standard” route where they operate during the rest of the year. This function is especially developed for routes, which are due to environmental conditions only usable for part of the year like arctic passages. For this reason the model is also capable of implementing ice data for the route and simulating ships performance in both, open water and ice. Furthermore, the model is able to simulate slow steaming, what can be from particular interest for liner operation, because of the high potential of fuel savings. The main output of the model is the cost per transported TEU between two destination ports transported by a specific vessel operating at a certain route for the vessels lifetime. By running the simulation for several routes and vessels the economically best solution can be found. In addition, the potential profit over the ships lifetime can be roughly estimated.

The functionality of the SBDS-tool is simplified illustrated in Fig. 11. The different steps for a combined route, consisting of Route 1 and Route 2, are shown. In case a ship is operating on a year round basis on the same route, in step 2 of the model only one side is used, depending if there is ice occurring along the route. In the following section, the individual steps of the model are explained.

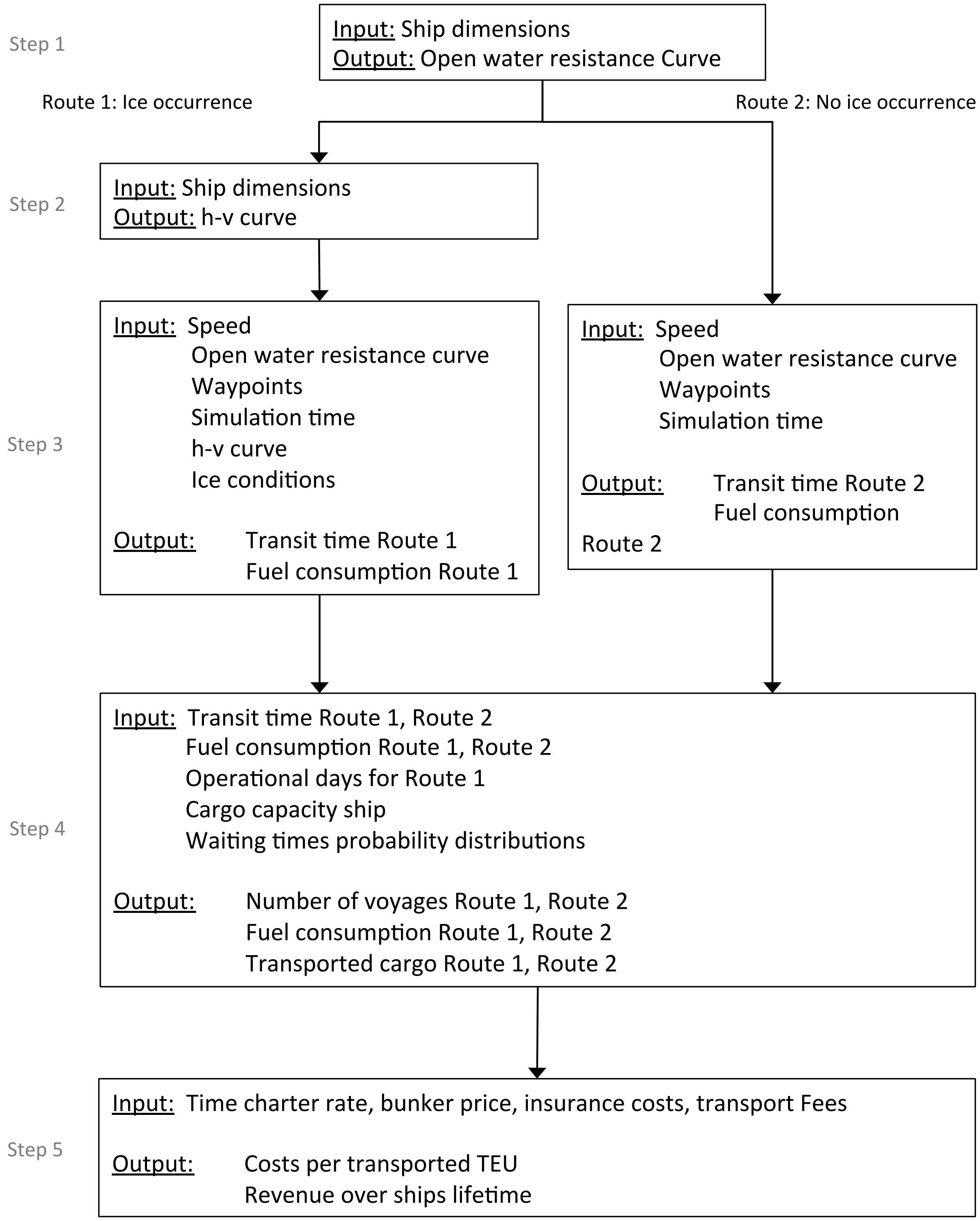


Fig. 11: Scheme of the developed model

Generation of the open water resistance curve (Step 1):

In the first step, the dimensions for a specific vessel have to be entered in the model in Microsoft Excel. Then several points are calculated for the open water resistance. A curve is fitted through them by using the Matlab Curve Fitting toolbox and the finished open water resistance curve is the result.

Evaluation of ship's ice performance and generation of h-v curve (Step 2):

Step 2 is calculating the ship's performance in ice is and is therefore only carried out in case ice occurs along the route. In order to obtain the h-v curve, a Matlab script, prepared for the Sustainable Arctic Sea Transport module at NTNU Trondheim by Sandro Erceg is used. The script was originally developed for level ice conditions and has been adapted to brash ice resistance in this thesis.

Calculation of transit times and fuel consumptions (Step 3):

The input parameters for step 3 are the waypoints in latitude/longitude coordinates of the route(s), input speed of the vessel, open water resistance curve and simulation time. In addition, the previously calculated h-v curve and the ice conditions are required if ice occurs along the route. Depending on this, also the procedure of calculating the transit times and corresponding fuel consumption varies as shown below.

The first step, that is the same for both, is the division of the route(s) in smaller sections, also called legs. Therefore the Matlab mapping tool is used to calculate the distances between the waypoints. Then the transit time and fuel consumption for every single leg is calculated. In case ice occurs the procedure looks like this:

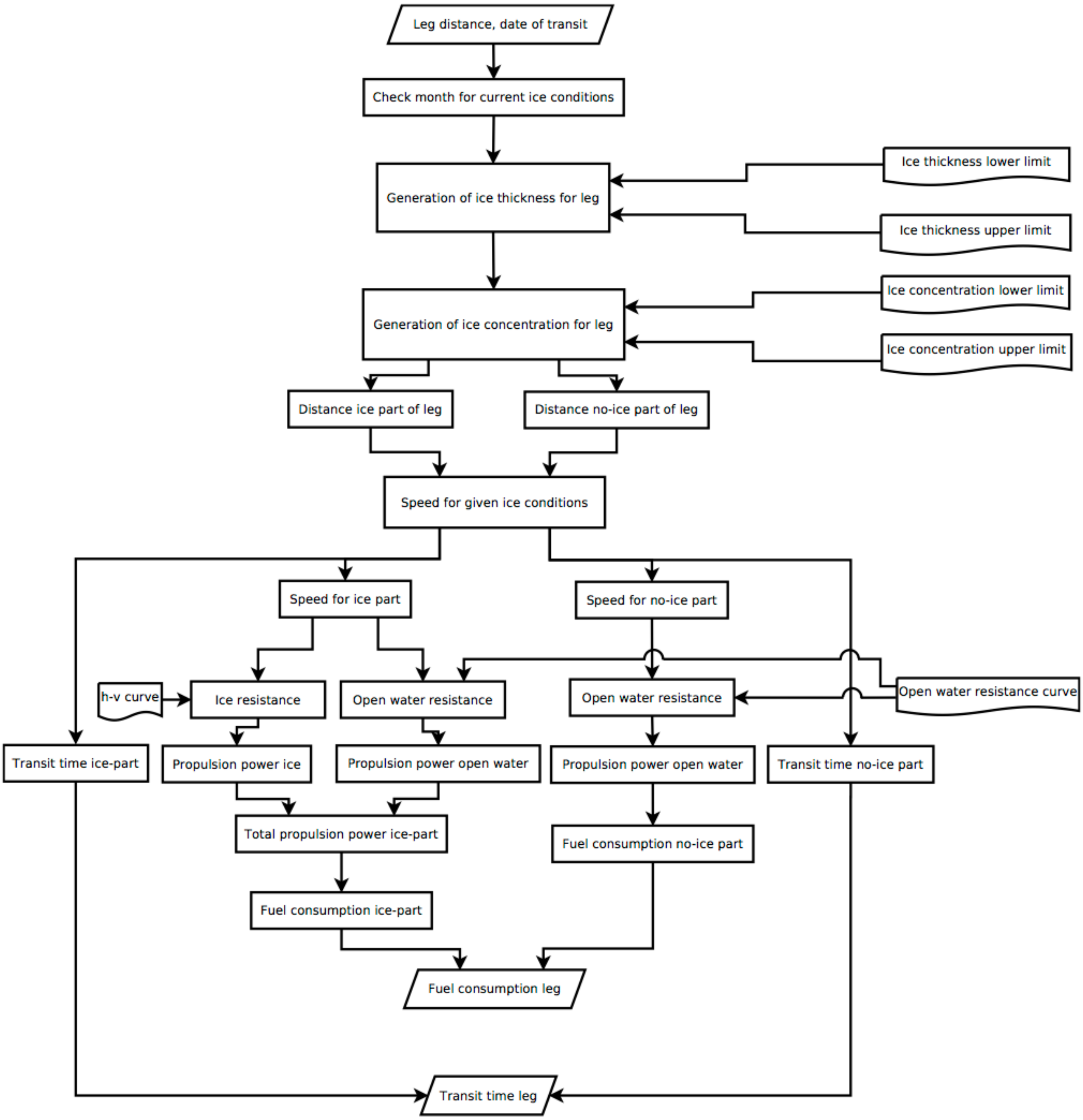


Fig. 12: Transit time and fuel consumption calculation

First, the current month is determined in order to load the corresponding ice conditions. These are in form of a lower limit and upper limit for ice concentration and lower limit and upper limit for ice thickness available. Between these limits for a specific date and leg a value for the ice thickness according to a probability distribution is generated. In Fig. 13 this is illustrated as an example for the generation of ice thickness along the whole NSR. The same procedure is followed for the generation of the ice concentration as shown in Fig. 14.

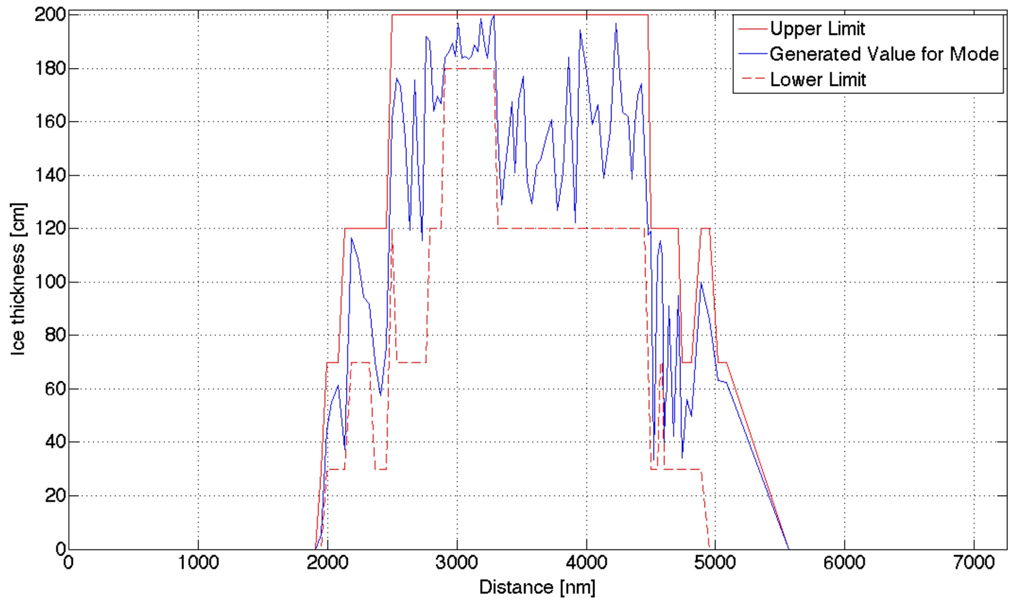


Fig. 13: Ice thickness generation between limits according to probability distribution

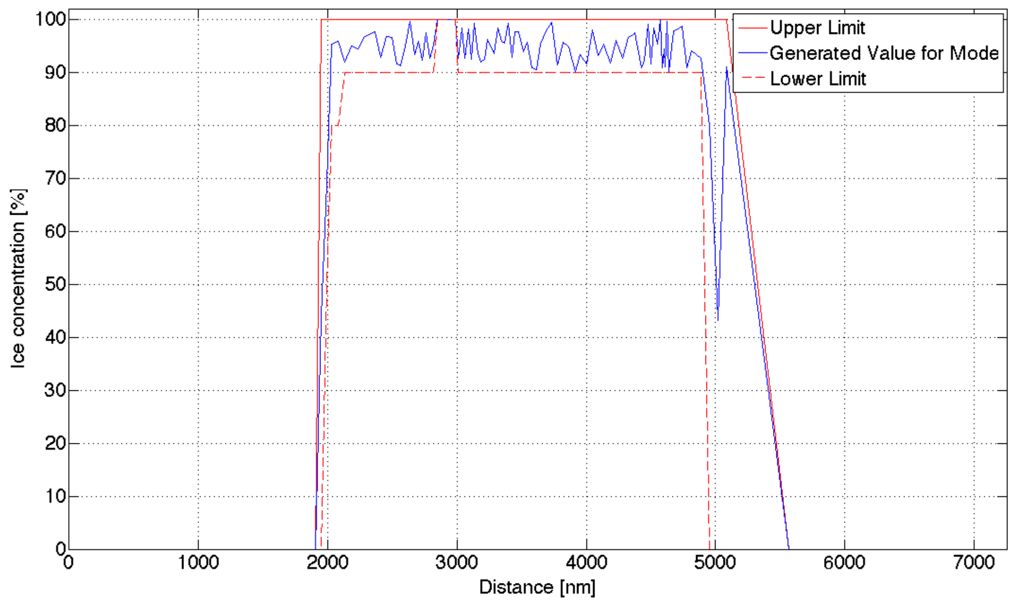


Fig. 14: Ice concentration generation between limits according to probability distribution

The multiplication of the ice concentration value with the leg distance gives the distance of the leg with ice coverage. For example, for an ice concentration of 60 % and 100 nautical miles (nm) leg distance, 60 nm are with ice and 40 nm are without ice. In the next step, the speed for the ice part and the speed for the no-ice part is chosen, respectively computed. This is done by the procedure shown in Fig. 15, which is applied on the example of the NSR. The underlying assumptions for this example are explained later in the case study chapter.

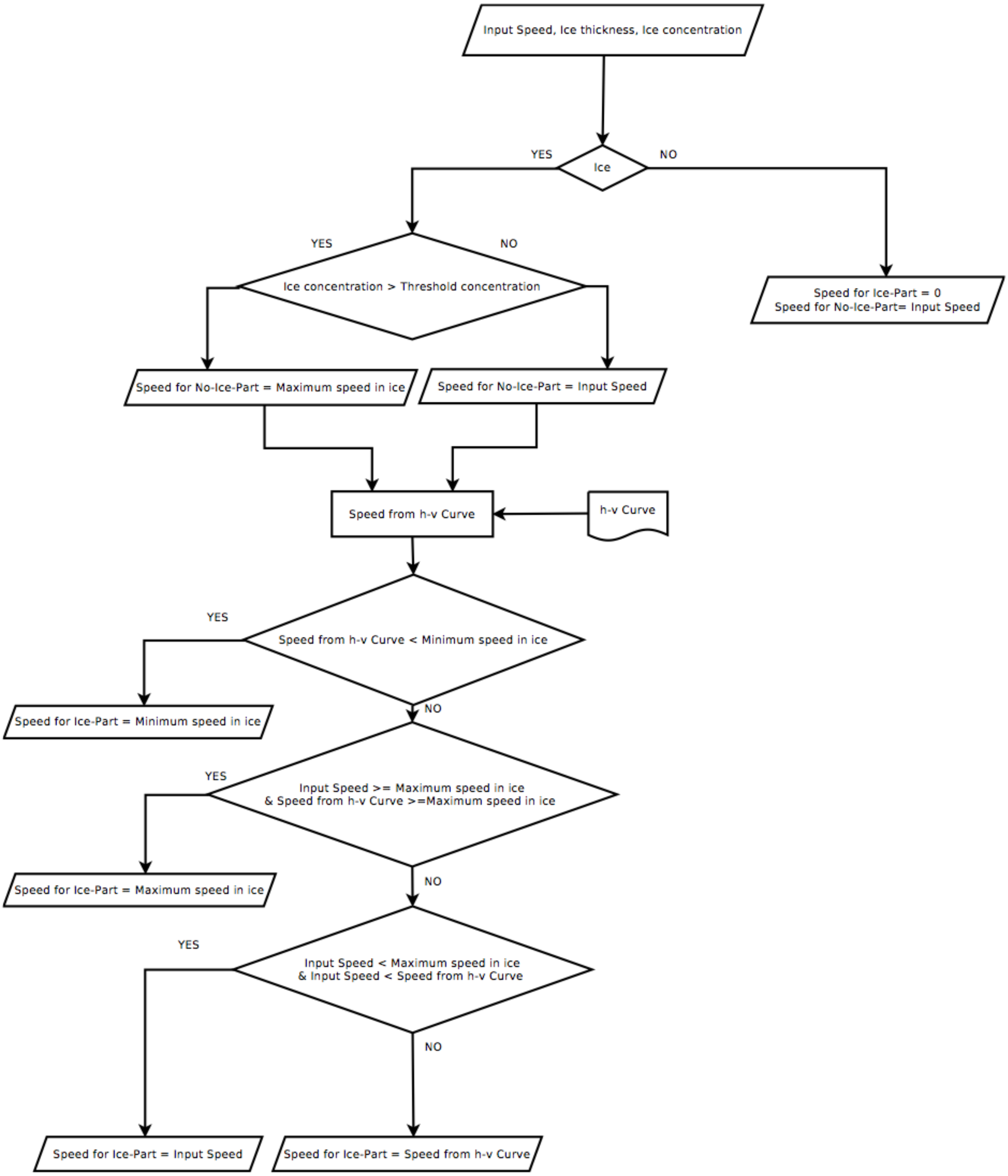


Fig. 15: Procedure for the speed selection for ice and no-ice part

From these the transit time for the ice part and for the no-ice part and consequently the total transit time is calculated. Simultaneously the ice resistance and open water resistance for the ice part is computed. Then the necessary propulsion power for both is obtained and added. Next the fuel consumption for the ice part of the leg is determined. The same procedure with only the open water resistance is applied for the no-ice part of the route. In the last step the total fuel consumption for the leg is obtained by adding the fuel consumption of the ice and of the no ice part.

The described method is applied for every leg of the route. Finally, the transit times and fuel consumption of all legs are summed up to the total transit time and total fuel consumption respectively. This information represents the transit information for a specific date and route of the simulation. Since this is needed for every day of the simulation as many datasets as the simulation time are generated.

For an ice-free route some parts of the just described method are not applying due to the lack of ice. Therefore, the procedure becomes simpler as shown in Fig. 16.

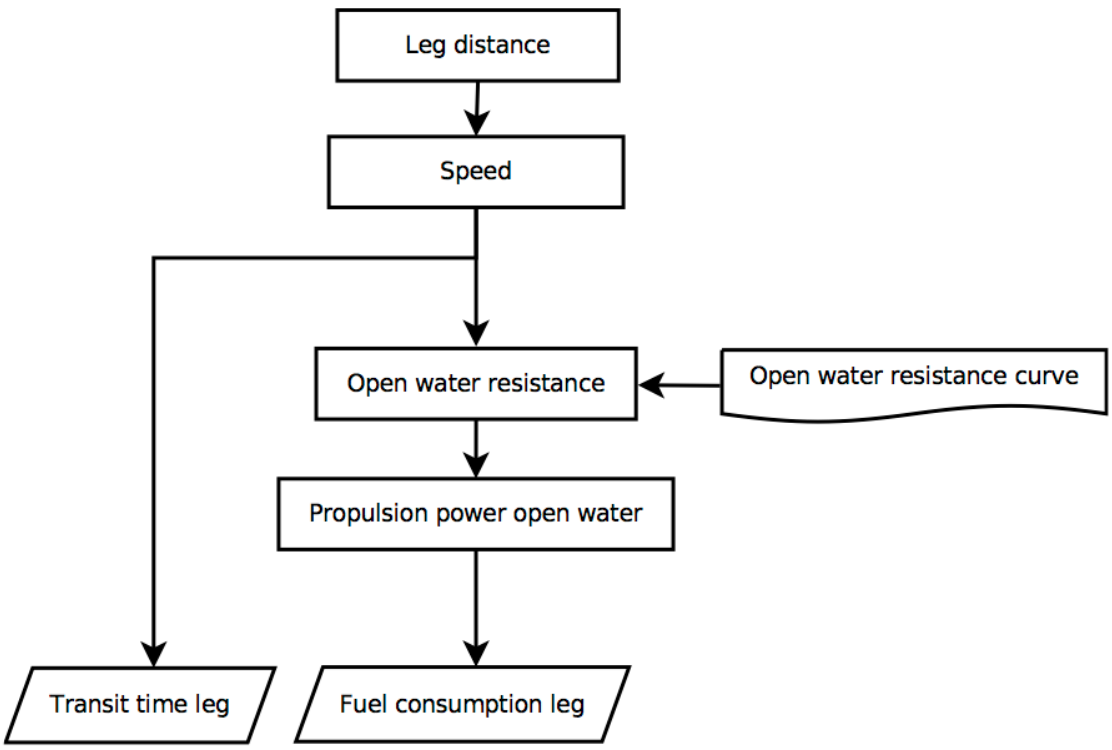


Fig. 16: Procedure for the speed selection for an ice-free route

Operational simulation model (Step 4):

In the previous steps, all the necessary information was generated in order to simulate, in step 4, the vessels operation over its lifetime. For this purpose, a discrete event simulation model in the Matlab Tool Simevents has been developed. The general concept of the operational model is presented in Fig. 17. It shows the two ports Port 1 and Port 2 between which the ship is operating and delivering cargo. The four connections between the ports represent the different route options a ship can go. One outbound and inbound connection together represents one route. The model is capable of combining these two routes. The ship operates partly on Route 1 and partly on Route 2. The user defines the decision rule at what point a route is used. The standard preference is depending on the time of the year. That means that normally Route 1 is used and for a certain time period of the year Route 2 is used. This function is in particular designed for routes that are only useable for part of the year like the ones in ice-covered water. Nevertheless, it is also possible to simulate only operation along one route. The simulation starts with the creation of one or more ships in Port 1. Then the ship is choosing the outbound route depending on the conditions described above. According to the simulation time the corresponding sailing times are loaded. In addition, a route specific waiting time is added e.g. waiting in front of Suez Canal or for icebreaker support. After accomplishing the journey, the ship is arriving in Port 2 where it is first waiting for docking and then the cargo is unloaded and new cargo is loaded. Then the same route procedure is carried out once more. First the route decision is made and then the ship is sailing including waiting times along the route inbound to Port 2. There the ship has to wait again for unloading and loading. After getting the new cargo load the whole process starts from the beginning except the ship creation part since this is only carried out once in the beginning of the simulation. In the following section the detailed activities in the model are explained step by step.

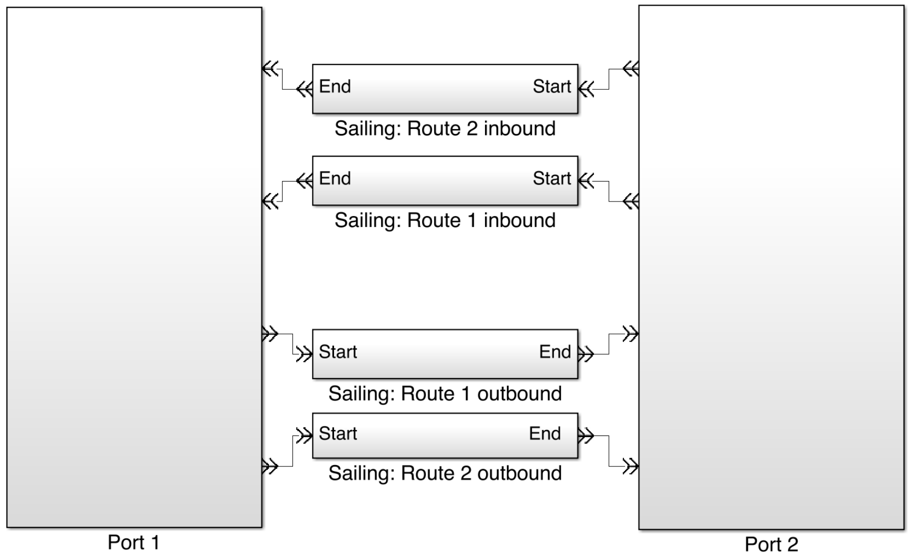


Fig. 17: Operational model in Simevents

Port 1:

The SimEvents simulation starts with the creation of one or more ships in Port 1, as shown in Fig. 18. The subsystem in detail is illustrated in Fig. 19. The very first SimEvents block 'Time-Based Function-Call Generator" generates a signal at simulation start for the creation of a ship. The ship is created in the next block 'Event-Based Entity Generator' as 'Entity'. An entity is representing one ship with different attributes. The following block 'Start delay for catching Route 2 time window' is an optional possibility for delaying the ship in the beginning so that it can catch exactly the first day when Route 2 is open. However this option is not used in the following case study. The 'Instantaneous Entity Counting Scope' displays the number of generated ships in a figure and is not relevant for the model itself. The same applies to all the blocks with 'Output' in the name. Their task is to export the simulation results to the Matlab Workspace for further analysis. In the next step, the vessel properties are assigned to the ship. This means that the cargo capacity, sailing time, fuel consumption, waiting time on Route 1, waiting time on Route 2, the route decision, sailing time without waiting times and the port service time are defined. All attributes except the cargo capacity, which is set to an initial value, are set to zero in the beginning. They are meant as intermediate storage of transit information until the end of the transit, and then their values are exported to the Matlab Workspace. The parallel series of blocks next to the just described ones represent a second ship creation line as optional possibility for creating more ships. In case of use the ‘Path Combiner’ has to be connected to the adjacent blocks.

After completed creation of one or more ships, the entity is passing a ‘Path Combiner’ block that connects the outbound route and the inbound route so that a round-trip is possible. In the next series of blocks the current simulation time is requested by the ‘Clock’ and then set to an attribute. The attribute function is containing the decision rule for the selection of the route. Therefore it will be checked if the current time is contained in the time window for Route 2 or Route 1. Depending on this decision, the ship is sent on the right route in the ‘Output Switch’ block.

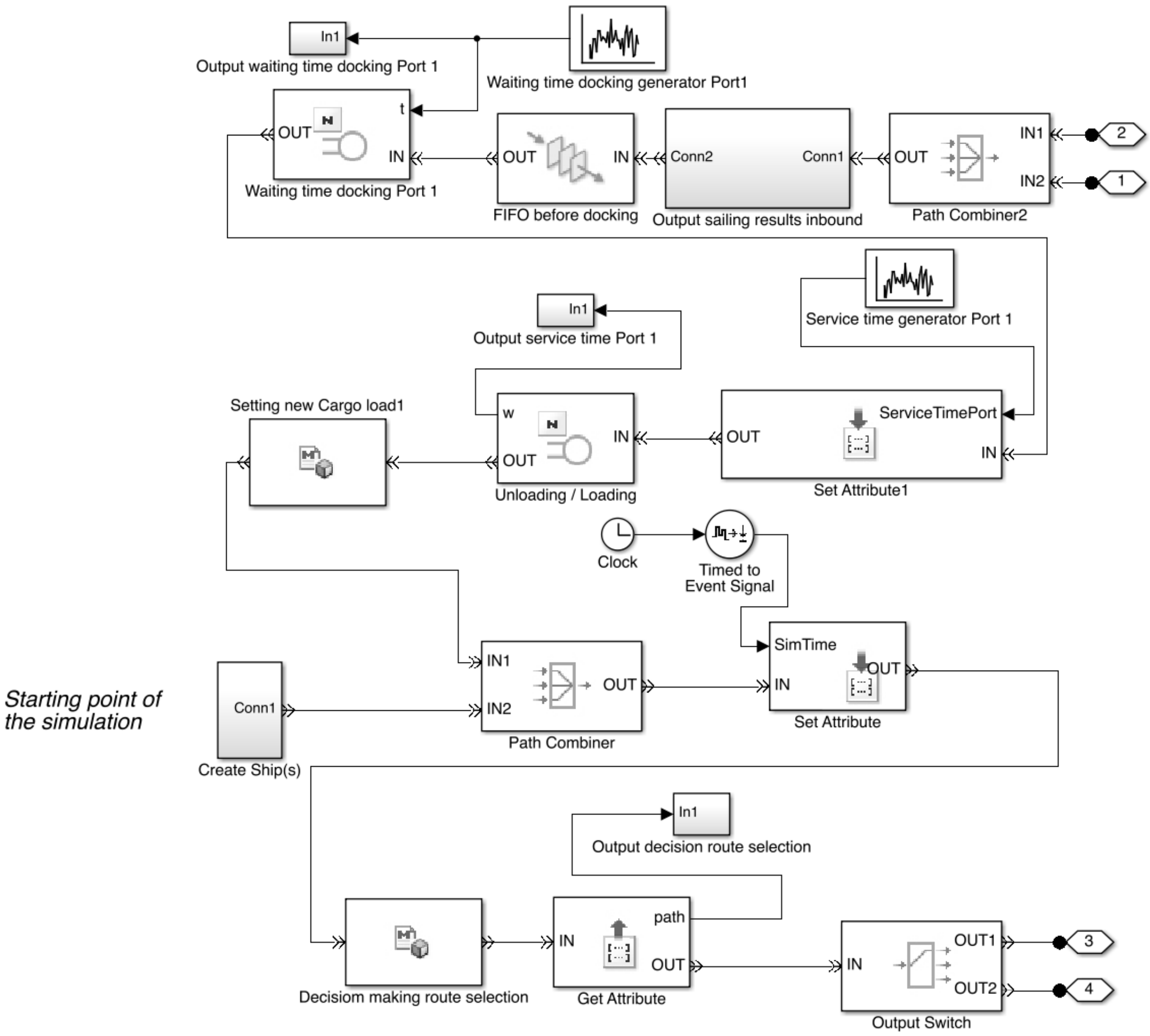


Fig. 18: Port 1

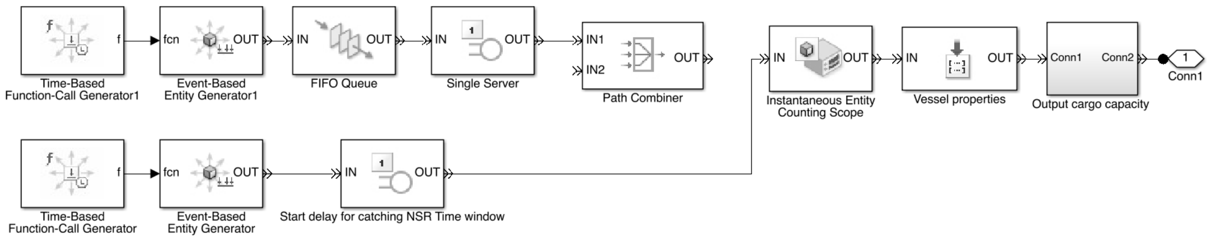


Fig. 19: Port 1 subsystem 'Create Ship(s)'

Route:

When the ship is reaching the first block of the entered route a waiting time is generated in the 'Waiting Time Generator Route 1'. This can be depending on the real route for example the time ships have to wait for entry of the Suez Canal or the waiting time for icebreaker assistance. In addition, the current time is requested. Both are set as an attribute and fed as input in the Matlab function block 'Sailing time calculation Route 1 outbound'. The function loads for the current simulation time the corresponding transit time and fuel consumption. This information is set as attributes in the next block. The parallel 'Infinite Server' block is necessary for the correct functionality of the model and has otherwise no function. The 'Sailing Route 1 outbound' is a SimEvents Server block and the ship spends the defined sailing time there before the ship can go further. In the last block of the route the obtained results are exported to Matlab workspace. The routes Route 1 and Route 2, outbound and inbound, are completely identical in terms of structure and functionality. The only difference lies in the 'tuning' of the route, that means the selection of the probability distribution and belonging parameters for the 'Waiting Time Generator' and the input files for sailing time and fuel consumption that were created in the previous step of the overall model.

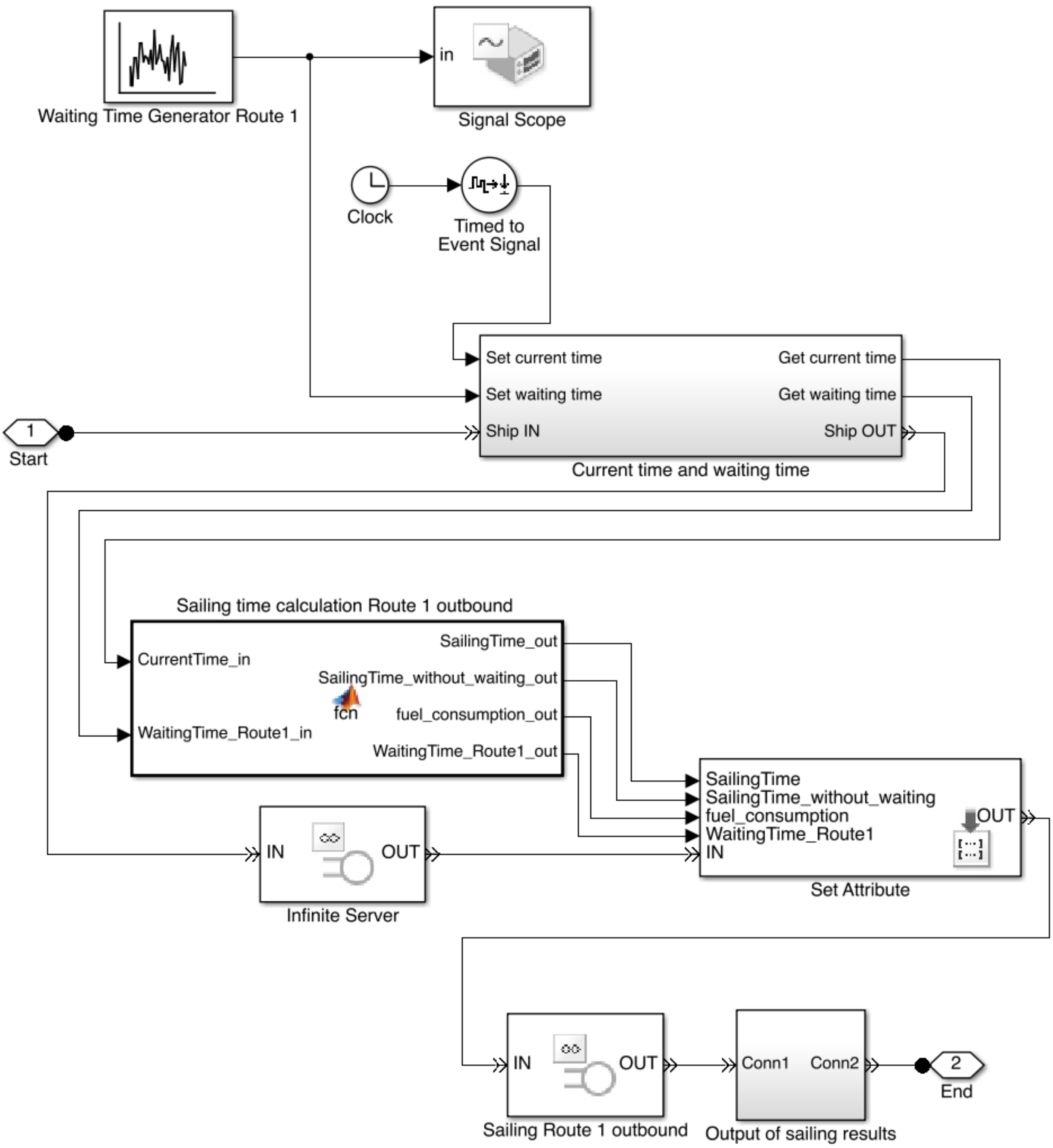


Fig. 20: Route 1

Port 2:

In Port 2 the two routes are united again in the ‘Path Combiner1’ and in the next block the sailing results for both outbound routes are obtained. The following block is a First-In-First-Out queuing block. That means that the ships are waiting in line, in or outside the port, for docking. The ship that arrived first has the right to go first for docking while the others have to wait for their turn. Then the ‘Waiting time generator docking Port 2’ generates a docking time according to a selected probability distribution. Consequently, the ship has to wait this time in the ‘Waiting time docking’ block. In the next step a service time, again according to a probability distribution, for the unloading and loading of the ship with cargo is generated and spent in the 'Unloading/Loading' Server block. Then the new cargo load is set. This gives the possibility of selecting different cargo loads outbound and inbound in order to make the model more realistic. For example is for a ship operating between Europe and Asia the degree of capacity utilization much higher westbound than eastbound. In order to take this into consideration this function has been implemented. The block 'Setting SailingTime=0' sets, as the name of the block already indicates, the sailing time to zero. The following blocks and their function for the route selection were already described earlier and therefore further explanations are skipped at this point. The ship enters then a route inbounds and arrives at Port 1 and a full roundtrip has been successfully completed. This simulation sequence is repeated until the end of the simulation time. The gained results of the simulation: the number of voyages, the fuel consumption and the transported cargo along the routes serve as input for the next step of the overall model that is evaluating the economic perspective.

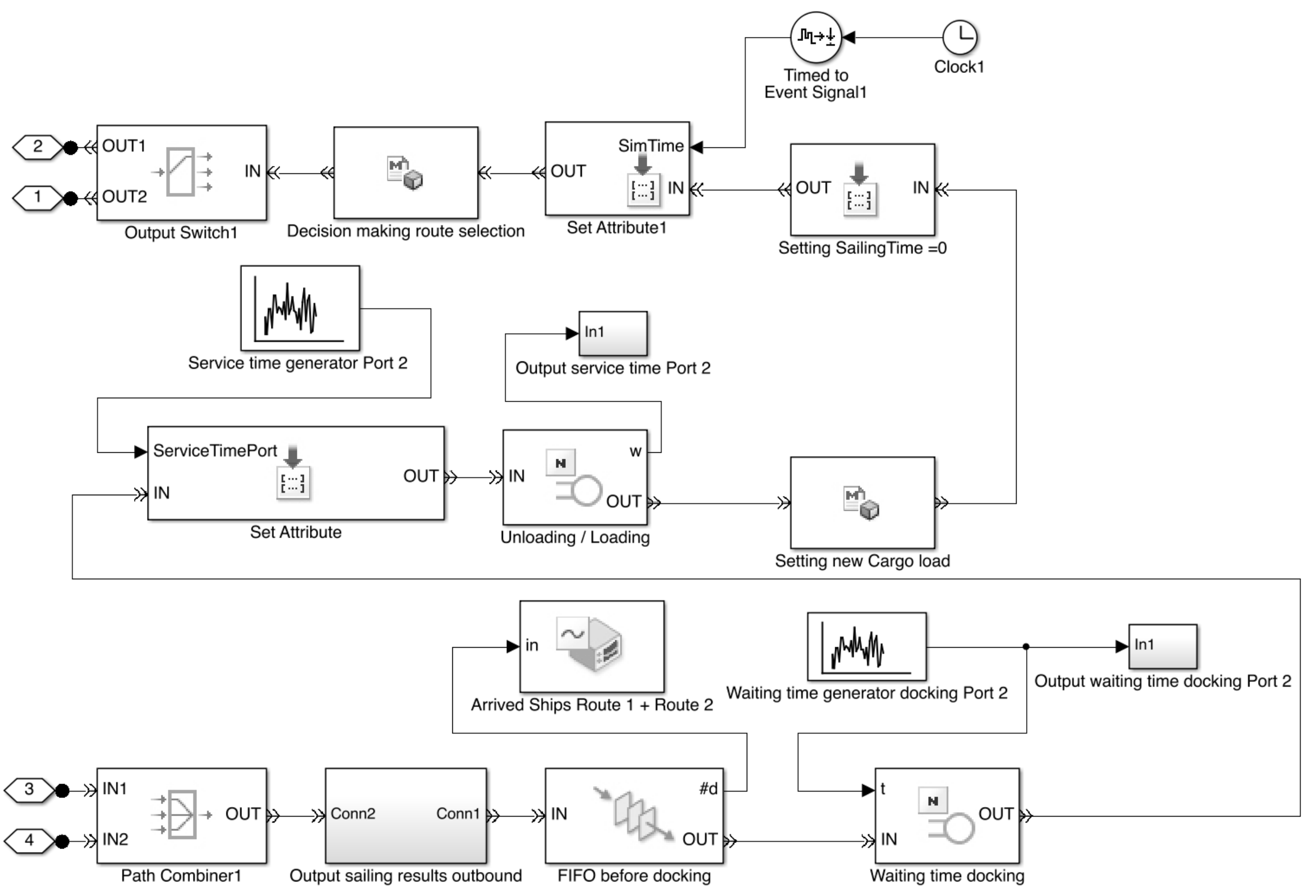


Fig. 21: Port 2

Economic Analysis (Step 5):

The result of the economic analysis is the cost per transported TEU cargo between two ports for the specific input. Based on this value the different options can be compared and the most cost efficient option to transport cargo under the given assumptions can be identified.

After the operational simulation of the ships lifetime it is known how many times the ship takes which route and how much fuel it consumes for this. Furthermore, the transported cargo is known. An example for the results from the operational simulation model for a combined route is shown in Table 2. In order to get the cost per transported TEU cargo, general costs for operating the vessel have to be introduced first. These include the rate for the chartering of the vessel, insurance costs for the different routes, route-specific fairway fees like canal fees or icebreaker-support fees and the bunker price. An example for the introduced costs in the case study, where a vessel is operating at the NSR and SCR, is illustrated in Table 5. In the next step the total time charter rate over the ships lifetime is calculated, then the route-specific insurance costs and fairway fees are multiplied by the number of voyages for the corresponding route and the total fuel consumption is multiplied by the bunker price. All these costs are then summed up and divided by the transported cargo in this time.

The described procedure is done automatically when the results from Matlab are imported to Microsoft Excel. When this is done for several different scenarios the costs per transported TEU can be compared and discussed.

Table 2: Example for the results of the operational simulation model

Voyages		
Route 1 - outbound		40
Route 1 - inbound		28
Route 1 - total		68
Route 2 - outbound		140
Route 2 - inbound		151
Route 2 - total		291
Total		359
Total covered distance	[nm]	3779061
Fuel consumption		
Route 1 - outbound	[t]	70452
Route 1 - inbound	[t]	49795
Route 1 - total	[t]	120247
Route 2 - outbound	[t]	375902
Route 2 - inbound	[t]	405675
Route 2 - total	[t]	781577
Total	[t]	901824
Transported cargo		
Route 1 - eastbound	[TEU]	176080
Route 1 - westbound	[TEU]	123256
Route 1 - total	[TEU]	299336
Route 2 - eastbound	[TEU]	616280
Route 2 - westbound	[TEU]	664702
Route 2 - total	[TEU]	1280982
Total	[TEU]	1580318

To summarize, this chapter presented the developed SBDS-tool that makes it possible to compare different route options. The single steps were explained in detail, giving an insight in the input, output and functionality of the SBDS-tool. These included the generation of the open water resistance curve, day-specific ice conditions and h-v curve for the vessels speed in ice. With this information, the day-specific transit time and fuel consumption for a vessel can be calculated. Then the operational simulation for the vessels lifetime was explained. In the last part the economic analysis was discussed. In the following chapter the SBDS-tool is applied on a case study for container shipping along the NSR and SCR serving the ports of Rotterdam and Yokohama.

5 Case study

This case study compares three different ships and assesses their performance on a route between Rotterdam and Yokohama. For this purpose, the developed SBDS-tool is used to evaluate the ships performance in point of revenue and costs over the ships lifetime of 20 years. Two of the ships operate at the NSR on a seasonal basis and on the SCR the rest of the year. The third ship is serving as a reference vessel that is representing the currently established transport system. This vessel is operating exclusively at the SCR.

5.1 Ship selection

The main parameters and additional parameters for calculation of the ice resistance of above mentioned ships are presented in Table 3. The two larger of the vessels are based on existing ships and the small one is based on an existing design concept. The given names consist of ‘CV’ that stands for ‘Container Vessel’ and the cargo capacity of the vessel in Twenty-Foot-Equivalent. The ships are selected according to vessel restrictions on the routes they are operating. For the NSR this is mainly the draught limitation of 15 m and a width limitation depending on the number of icebreakers assisting the ship in ice (Melenas 2013). The present nuclear icebreaker fleet has a width of 30 m and creates a slightly larger channel (Barentsobserver 2013). With support of two icebreakers also ships with a larger beam are able to sail the NSR. Therefore this criterion is setting only partially limitations, although it can be expected that the charged fees increase significantly with the use of two nuclear icebreakers. The Suez Canal is setting the limitations for the southern route. There a maximum draught of 20.1 m and a width of 50 m apply, allowing much larger vessels to transit (Suez Canal Authority 4 2010). Thus, the following vessels are used:

1. CV 2300: The ship is a container feeder vessel with a capacity of 2300 TEU. It doesn’t hold an ice class and is therefore more sensitive to ice occurrence. The beam of 30.4 m is slightly wider than the one of a present nuclear icebreaker, but since the created channel is usually a bit wider it is assumed that it can follow them. Furthermore, the channel width is going to increase to 34 m with the commission of the new nuclear icebreakers in 2017

(Barentsobserver 2013). This vessel is based on the ‘SeaDragon’ design concept of Grontmij (Grontmij 2012), a European engineering consultancy company.

2. CV 4400 ICE: This container ship is based on the existing vessel OOCL Montreal, which is operating between North America and Europe (OOCL Group 2014). Since the Great Lakes are part of the ship’s trading area and in winter they are usually ice covered, it is holding the ice class 1C. It has been chosen because of the fact that it is one of the largest existing container vessels holding an ice class. The beam of 32.32 m (grosstonnage.com 2014) makes it necessary to have two of the present nuclear icebreakers, or one of the future-type, in front of the ship if the ice conditions are heavy.

3. CV 8160: This container ship is based on the existing vessel Sofie Maersk (Mærsk A/S 2014). It is operating between Europa and Asia via the Suez Canal and is therefore used as reference vessel. In the model this ship is exclusively using the SCR.

Table 3: Parameters of the vessels (grosstonnage.com 2014)

Ship		CV 2300	CV 4400 ICE	CV 8160
Length	[m]	185	294	346
Beam	[m]	30.4	32.3	42.8
Draught	[m]	8.5	10.8	14.9
Displacement	[t]	30472	63220	141243
Deadweight	[t]	20800	47840	110381
Payload	[TEU]	2300	4402	8160
Gross tonnage	[t]	25600	55994	92198
Speed open water (Service)	[kn]	19.0	25.2	24.6
Propulsion power	[kW]	12491	37275	55681
Total efficiency		0.853	0.878	0.700
Specific fuel consumption	[g/kWh]	180	180	180
Length parallel (L_{par})	[m]	92.5	147	-
Length bow (L_{bow})	[m]	46.3	73.5	-
Diameter propeller	[m]	5.1	6.6	-
Area waterfront (A_{wf})	[m^2]	703	1187	-
Propeller		1	1	-
Bulb		Yes	Yes	-
α	[°]	23	23	-
Stem angle (ϕ)	[°]	90	90	-

5.2 Route selection

In the case study, the NSR and the SCR from Rotterdam to Yokohama are integrated in the developed model. The Matlab model requires the route as latitude/longitude coordinates. The SCR coordinates are obtained from the ‘Dataloy Distance Table’ website, provided by Dataloy AS, a Norwegian company specialized on maritime software (Dataloy AS 2014). The so-defined route is shown in Fig. 22. The NSR coordinates and corresponding ice conditions are obtained from ‘Route 4’ Tõns defined in his paper ‘Ice condition database for the arctic sea’ (Tõns 2014). The route runs from the Barents Sea via the Kara Gate and north of the New Siberian Islands in the East Siberian Sea. However, these ‘core data’ cover only the Russian part of the NSR and not the whole distance from Rotterdam to Yokohama. It is the part of the route where ice occurrence is very likely and is represented by the blue part of the route in Fig. 23. The rest of the coordinates are obtained again from Dataloy Distance Table, described by the red part of the route. Since there is no exact overlap of the two routes in the area where they converge, the intermediate points are manually approximated, represented by the dashed red line. However, the explained procedure shows only the efforts to provide reasonable input data for the model and doesn’t mean that this is necessarily realistic in detail. Furthermore, the primary focus of this thesis lies on the development of the procedure to give stakeholders a tool to support their decisions. They have more detailed data themselves for input.

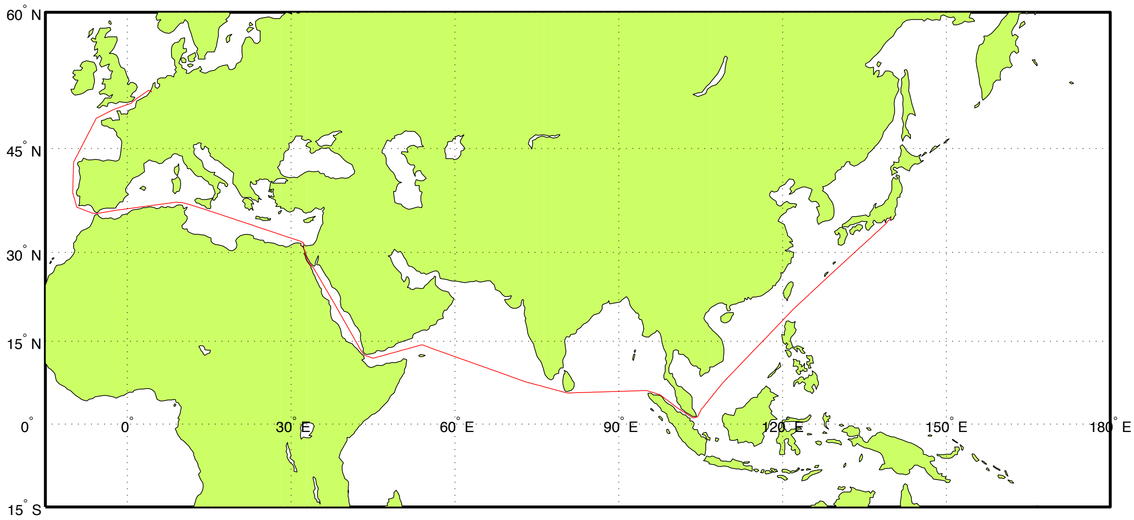


Fig. 22: Defined route for the SCR

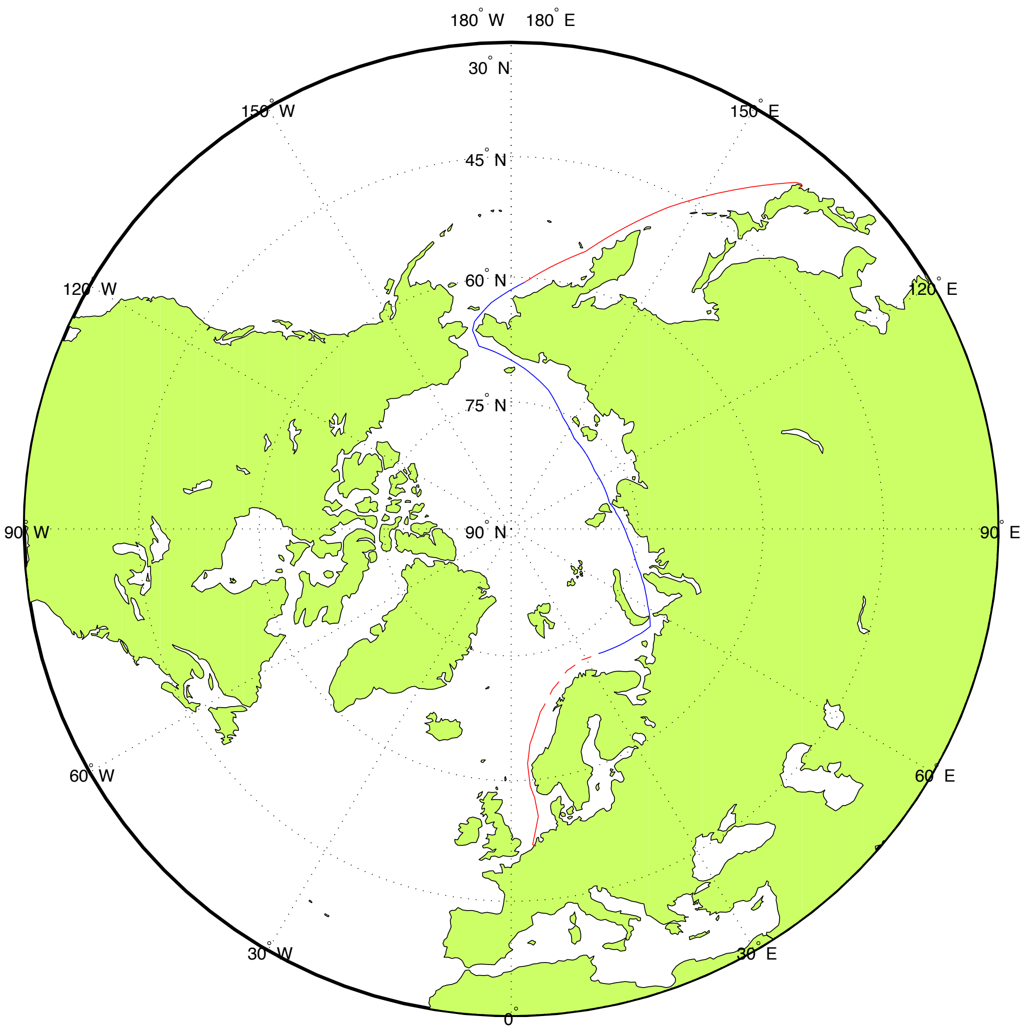


Fig. 23: Defined route for the NSR

5.3 Ice conditions along the route

The source of the ice conditions used in this thesis is ice data from NATICE satellite source (U.S. National Ice Center 2014) and was obtained by Tõns (Tõns 2014). The data contains large uncertainties and therefore it is not possible to find an exact value for the ice thickness and concentration for a certain waypoint at the observed time. Instead, a range is used to describe the ice conditions. That means that there is a maximum and a minimum for both thickness and concentration. This is due the type of observation. Analyses of satellite images provide the ice type data, not directly the ice thickness (Tõns 2014). Consequently the ice thickness is derived from the ice type. The data originates from 2008 and 2009. Before it was implemented in the model the data was edited as follows. The ice is assumed to be so-called first year ice. That means that this ice was newly formed in the year of observation, in contrary to multi-year ice, which survived at least one melting season. First year ice is usually softer and therefore it is easier for ships to operate in it. In addition, it normally doesn't get much thicker than 2 m. Therefore higher values of the data were set to this value. This assumption is based on figures from the Russian Arctic and Antarctic Institute shown in Fig. 24 (Arctic and Antarctic Research Institute 2009). There is shown that only first year ice occurred along the chosen route in the same year the ice data originates from. The detailed data serving as an input for the transit time and fuel consumption calculation is presented in the Appendix.

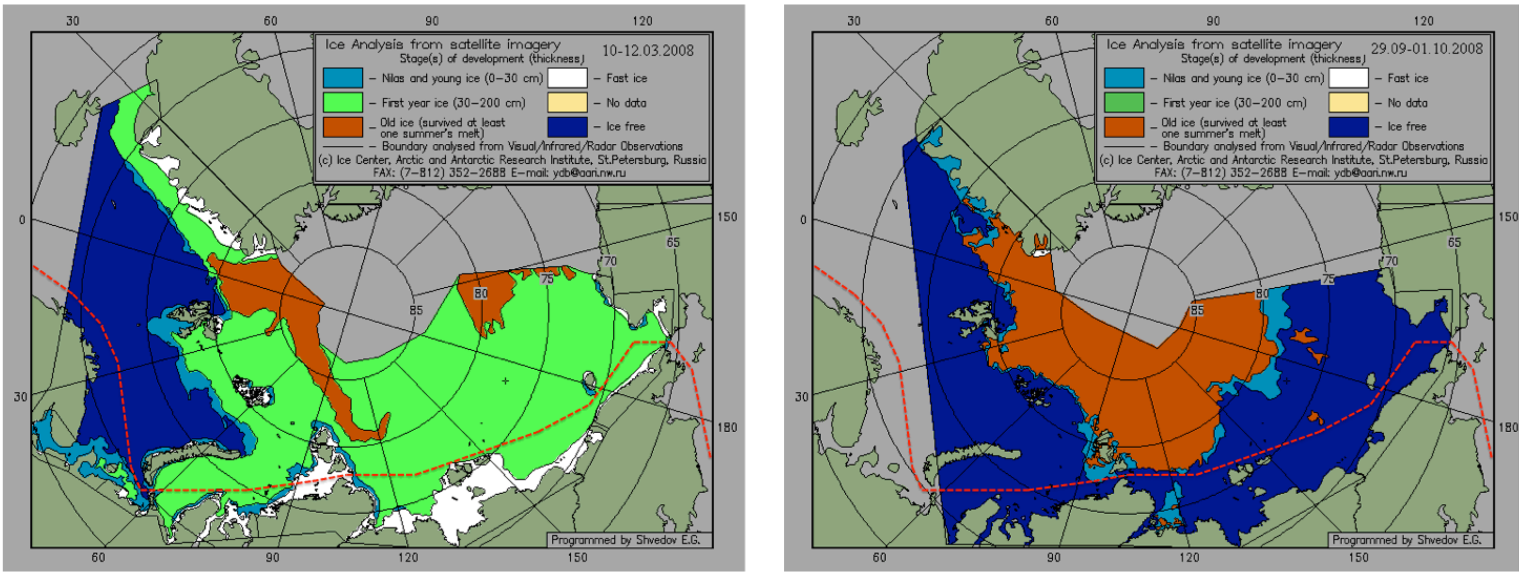


Fig. 24: NSR and observed ice conditions in March 2008 (left) and end September 2008 (right), adopted from (Arctic and Antarctic Research Institute 2009)

5.4 Time window for operation at the NSR

In this case study, the NSR is not used as a complete substitute to the SCR, but as an amendment. The decision when to use the NSR and when the SCR is mainly a matter of the ice conditions and Russian legislation. It is expected that the time with the least ice of the year is most beneficial to integrate in the transport system. As shown in Fig. 25 and in the used ice data in the appendix this are the month August, September, October and November. At this time of the year it is expected that the performance of the ship is highest and the lowest ice classes according to the Russian legislation are required.

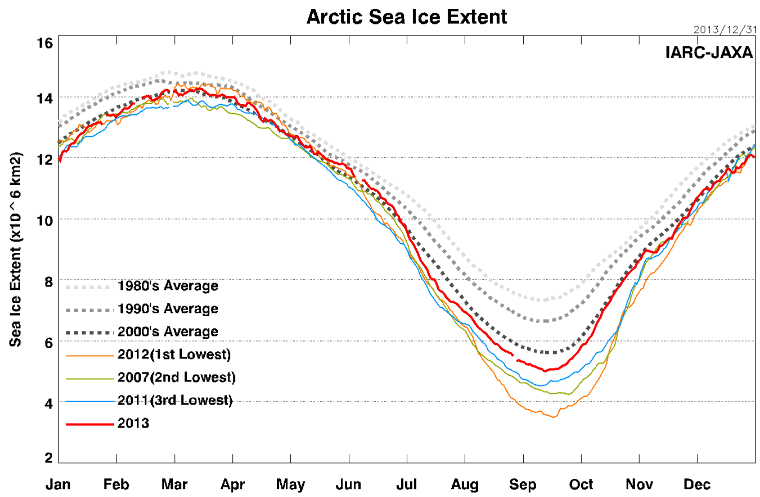


Fig. 25: Arctic sea ice extent

Based on this information three different time windows with 61, 92 and 122 days are assumed. These are the days of the year with least ice in the input data and consequently shortest transit times along the route. The time window is so defined so that during these days a ship is allowed to enter the NSR. It can enter the route on the last day of the time window and still complete the whole transit also when this needs longer.

5.5 Uncertainty consideration with respect to probability distributions

The developed decision support tool requires additional input for the generation of ice conditions, the waiting times along the routes and in port and the service time for unloading and loading of the ships. All these data are subject to great uncertainty. This is due the fact that long-term prediction of climate or environmental conditions is a very difficult task and by far not accurate science. The remaining parameters are indeed better to estimate, but the ‘real’ data is either a trade secret and therefore not publicly available or simply there is not enough data available yet to draw conclusions. The second described situation is for example applying for the waiting time for icebreaker support along the NSR. Nevertheless is the finding of data until the last accuracy not subject of this thesis. As a way to deal with this large uncertainty in the parameters, it was decided to use probability functions to also show the impact of the uncertainty on the final results. In Table 4 the used, assumed, probability functions are listed.

Table 4: List of probability functions used for the model

Model variable	Unit	Probability distribution	Parameters
Ice concentration	[%]	Uniform	a=lower limit ice concentration, b=upper limit ice concentration
Ice thickness	[m]	Uniform	a=lower limit ice thickness, b=upper limit ice thickness
Waiting time NSR	[h]	Weibull	Scale=20, shape=2
Waiting time Suez Canal	[h]	Weibull	Scale=8, shape=2
Waiting time docking	[d]	Weibull	Scale=0.05, shape=2
Port service time	[d]	Gaussian (Normal)	Mean: 1 (1.5 for CV 8160), standard deviation: 0.1
Speed in open water	[kn]	Gaussian (Normal)	Mean: input speed, standard deviation: 0.5
Speed in ice (in certain cases)	[kn]	Gaussian (Normal)	Mean: computed speed, standard deviation: 0.5

For both, ice concentration and ice thickness a uniform distribution has been chosen to generate the ice conditions along the route. This has been done in accordance with the assumptions in the INSROP working paper No. 45, where also a uniform distribution was assumed for the ice conditions (The International Northern Sea Route Programme 1996). However, this assumption is reflecting the great uncertainty of the data and it is possible that a different probability distribution would be a better approach to reflect the real conditions in nature. Furthermore, the range between the ice conditions are generated quite small since the lower and upper limit are very close to each other. According to Prof. Marchenko, professor for ice mechanics at the University Centre on Svalbard, it is then difficult to say something about the ice thickness distribution (Marchenko 2014).

The waiting times in the model are generated according to a Weibull distribution. Fig. 26 shows the chosen Weibull distribution for the waiting time for icebreaker support at the NSR.

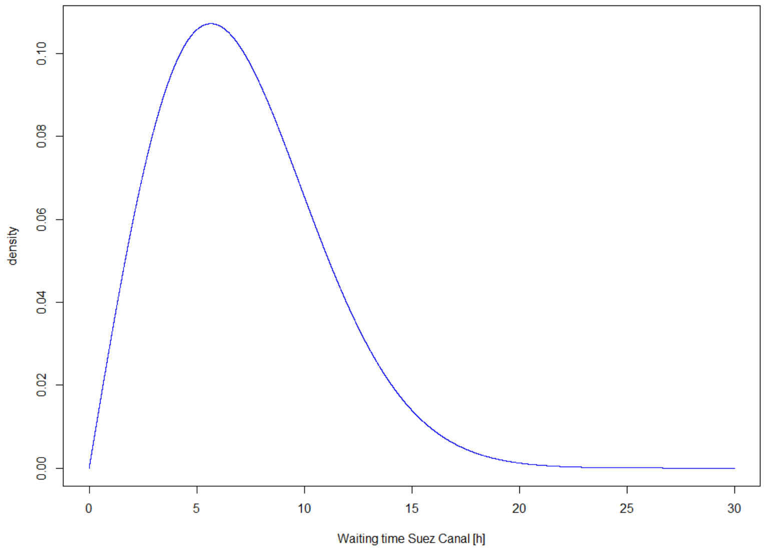


Fig. 26: Weibull distribution for the waiting time at the Suez Canal

For the port service time, the speed in open water and in certain cases also for the speed in ice a normal distribution is assumed. All used probability functions are based on very rough estimations and can be replaced if better data or more accurate information is available.

5.6 Introduced costs

The cost per transported TEU from Rotterdam to Yokohama or vice versa is used as unit to evaluate and compare the different transport options. The basic costs are listed in Table 5. The used time charter rates are obtained from the time charter department of Maersk Line. However vary the TC rates a lot over time, since market prices are very volatile (Maersk-Line 2014). The insurance costs for the SCR and the NSR are assumed. The Suez Canal fee is calculated with a formula from the Suez Canal Authority (Sørstrand 2012) and is therefore accurate to predict with little uncertainty. The opposite is true for the NSR tariffs, which are negotiated on an individual basis and therefore very hard to predict for the future. Furthermore will the long-term level of these be dependent on the total traffic volumes, supporting infrastructure like icebreakers and land based SAR facilities and political factors. However showed past negotiations that the fee can be bargained down to 5 USD/t

(Erikstad and Ehlers 2012). This value has been used as input for the calculations. The bunker price was set to 600 USD/t (bunkerworld.com 2014).

Table 5: Cost basis for the case study vessels

Ship		CV 2300	CV 4400 ICE	CV 8160
Time charter rate	[USD]	8500	27000	40000
Insurance SCR	[USD/voyage]	25000	40000	60000
Insurance NSR	[USD/voyage]	40000	50000	-
Suez Canal Fee	[USD/t]	4.30	3.40	2.95
NSR Fee	[USD/t]	5.00	5.00	-
Bunker price	[USD/t]	600	600	600

To sum up, in this chapter the case study was presented. The focus was on the input data for the developed SBDS- tool. Therefore the reasons for selecting the specific input were discussed, as well as the corresponding sources. The three case study ships and their dimensions, the selected routes and the corresponding ice conditions were introduced. Furthermore, it was explained during which time of the year it is most feasible to utilize the NSR. Last, the specific costs for the case study scenario were mentioned.

6 Results

In the following section, the results of the case study are presented and discussed. All the obtained values are based on the introduced assumptions of the previous chapter. Thus, the single results are not necessarily from general applicability, but since an attempt was made to keep the assumptions and data as realistic as possible the overall trends are expected to be suitable to support decisions for arctic transit transport. The costs per transported TEU between Rotterdam and Yokohama is chosen as performance indicator to determine if and under what conditions an economical beneficial transport system can be achieved.

In Fig. 27 the costs per transported TEU for the three case study vessels and the influence of the number of operational days along the NSR on it is illustrated. In addition the ice concentration is altered to show the impact of potentially less ice in the future. The solid green line stands for the CV 8160 reference vessel that is utilizing only the SCR and represents the current transportation system. Since this option is independent of operational days and ice conditions along the NSR it holds a constant value of around 476 USD. In order to be a profitable alternative, the other vessels operating partly on the NSR have to undercut this value. It can be seen that for the 100 % ice concentration scenario the CV 2300 and the CV 4400 ICE are not competitive in view of too high costs. Nevertheless, the CV 2300 vessel is able to transport cargo at significantly lower costs than its route competitor. The reason for this is the relatively much lower time charter rate of 8.500 USD compared with 27.000 USD. In contrast is the CV 4400 ICE vessel better in utilizing the NSR, since the slope of the line is declining faster. The ship's ice class and higher service speed of the vessel can explain this. With diminishing ice concentration both vessels catch up with the reference vessel. Still, the CV 4400 ICE stays also under the most favorable conditions of an ice-free route and an operational window of 122 days over the costs of the CV 8160. The CV 2300 reaches the area of savings for an ice concentration of 60 % of the original ice data and a minimum of 95 operational days. For 80 % ice concentration this "break-even point" is already reached at 70 operational days. In case the NSR is ice-free, the CV 2300 has always a better economic performance compared with the reference vessel ranging from three dollars at 61 days until notable savings of almost 30 USD at 122 days, what makes it competitive in comparison with the reference vessel.

The lowering of the ice concentration is resulting in a decline in costs for both vessels operating at the NSR, but when compared the influence is much higher on the CV 2300. This can be seen in Fig. 27 by the larger distances between the different lines for ice concentration variation. The explanation for this lies in the performance of the ship in ice. As it has no ice class it is much more affected by ice occurrence than the CV 4400 ICE with ice class 1-C. Nevertheless, if the ice becomes less it increases the performance of the ship by relatively large steps, because it is designed for open water conditions.

In Fig. 28 the ice thickness is varied. As can be recognized immediately the 100% and 0% ice scenario are the same as in the previous figure. When the two figures are analyzed in detail, it becomes clear that the reduction of the ice thickness has a much larger influence on the reduction of costs than the variation of the ice concentration. In addition, a first unexpected phenomena can be seen, namely that for the CV 2300 vessel the costs are lower if the ice thickness is 20 % of the initial value than at the no-ice scenario. A closer look on the case study and in particular how the speed of the vessel in ice is chosen reveals that a kind of “slow-steaming” effect is applying here. At the scenario with an ice thickness of 20 % the ice is very thin and the ship could go relatively fast in this ice according to the h-v curve, but the maximum speed is limited to 10 knots to ensure the integrity of the hull. Since the ship is going slower than it could the engine is operating at a lower load and it is saving fuel, which results in in lower overall transportation costs. Therefore the costs per transported TEU are lower compared with a completely ice-free route, where the ship is going with the maximum open water speed and, consequently, higher fuel consumption due to the higher power requirement.

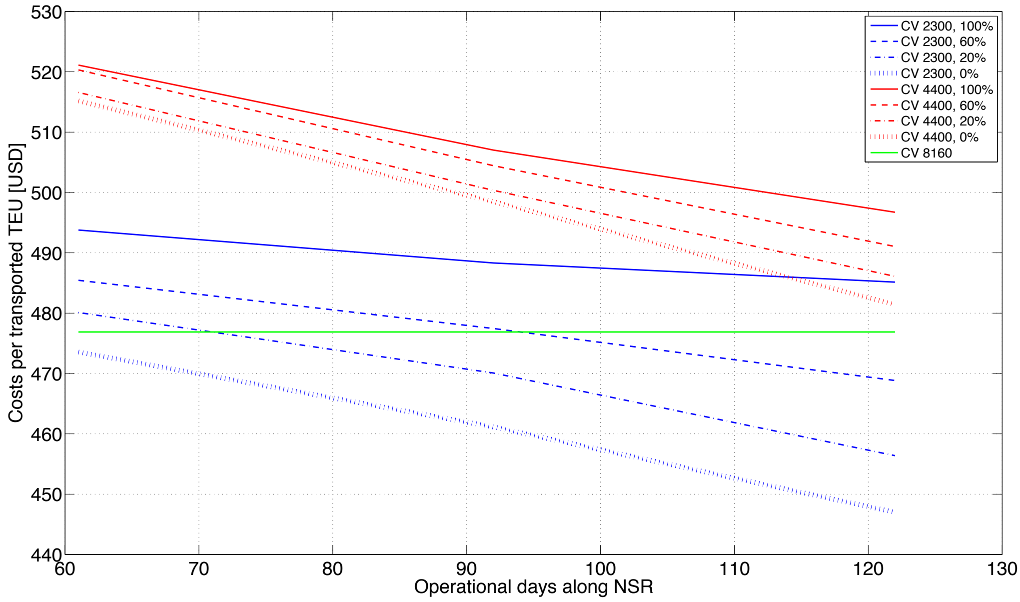


Fig. 27: Sensitivity analysis of operational days and ice concentration variation

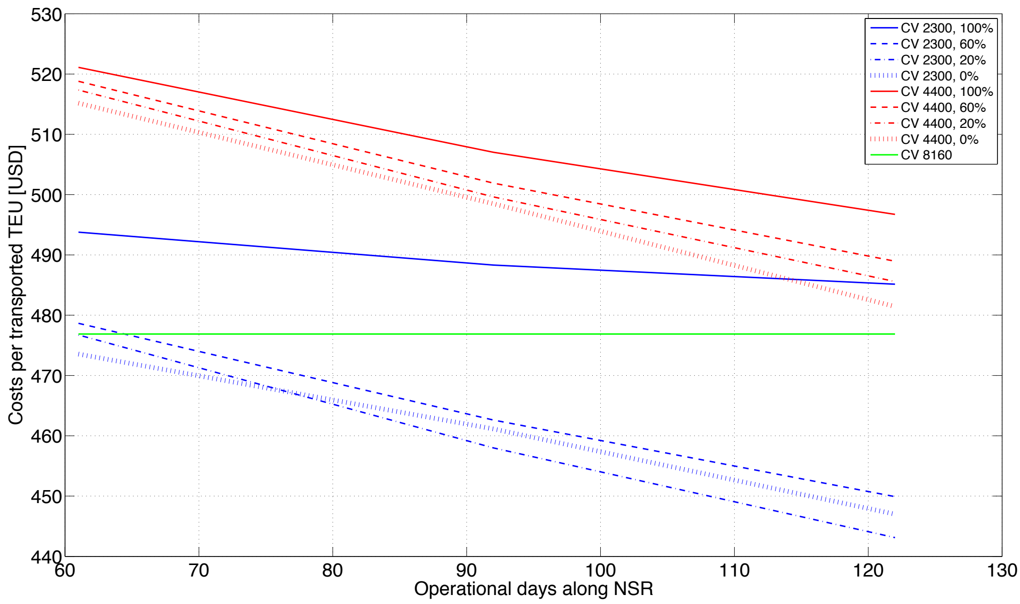


Fig. 28: Sensitivity analysis of operational days and ice thickness variation

As already mentioned, the NSR offers several opportunities when it is implemented in a schedule with the SCR. These are shorter sailing times associated with less capital commitment and additional time to balance delays or the possibility of using slow steaming. The last point is linked with the probably most important advantage of the NSR, the potential saving of fuel. Lower fuel costs are directly affecting the profitability of the route resulting in lower costs for transporting cargo. Therefore it is crucial to know under what conditions the fuel consumption per transported TEU is lower than for the reference vessel. This analysis is done in detail in Fig. 29. There can be seen that for the 100 % ice scenario the both NSR vessels need more fuel than the reference vessel. The fuel consumption per TEU of the CV 4400 ICE vessel stays for 61 operational days always over the CV 8160. The CV 2300 needs for an ice concentration of more than 65 % and 61 operational days more fuel than the reference vessel, but below this level small fuel savings are possible. For almost all other constellations significant fuel savings are possible. The amount of saved fuel is directly affecting the savings in cost per transported TEU, as shown in Fig. 30, where also the bunker price is taken into account. In general it can be said that the trend of the fuel savings is reinforced when put into cost considerations. In the different scenarios of Fig. 30 for ice conditions, operational days and bunker price and the implication on the final result are analyzed in detail.

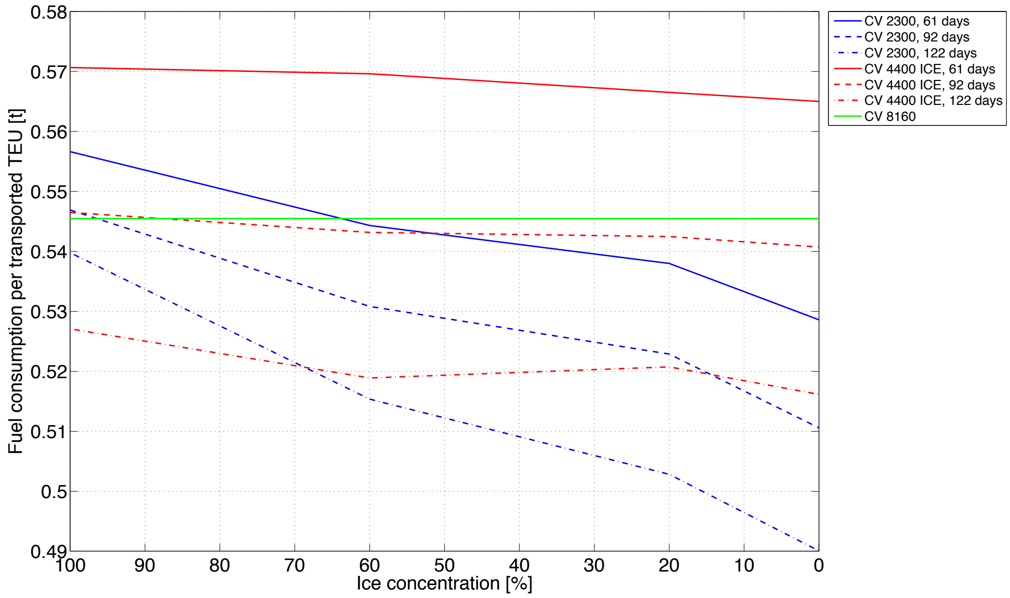
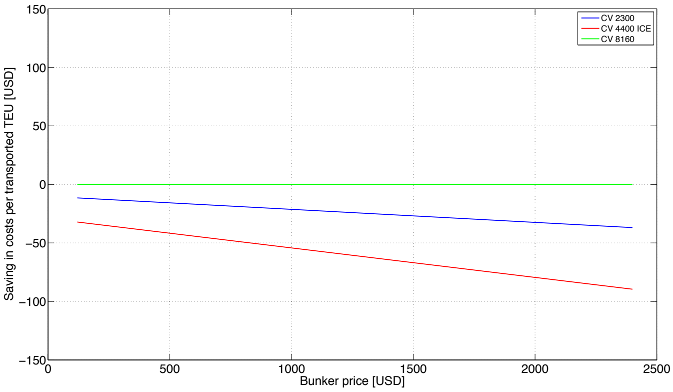
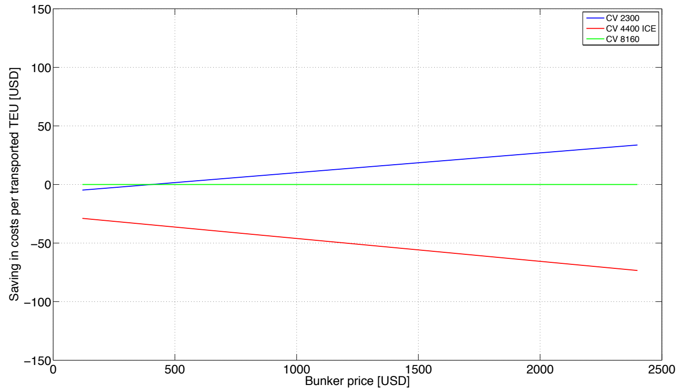


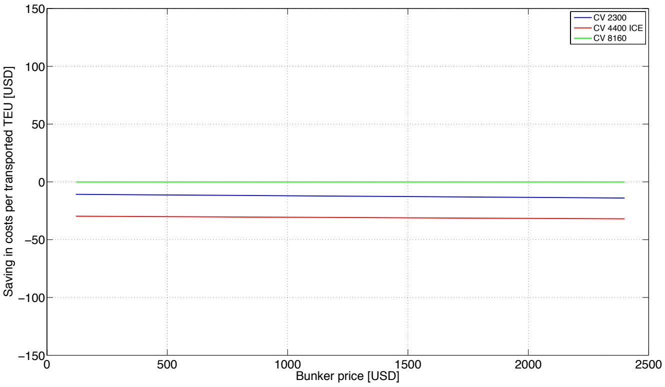
Fig. 29: Fuel consumption per transported TEU dependent on ice concentration and operational days



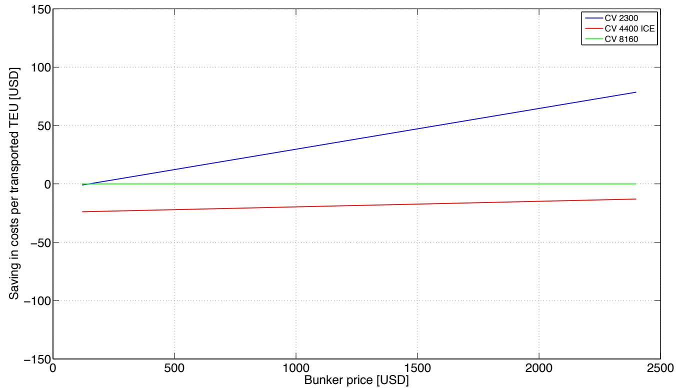
100 % ice scenario and 61 operational days along NSR



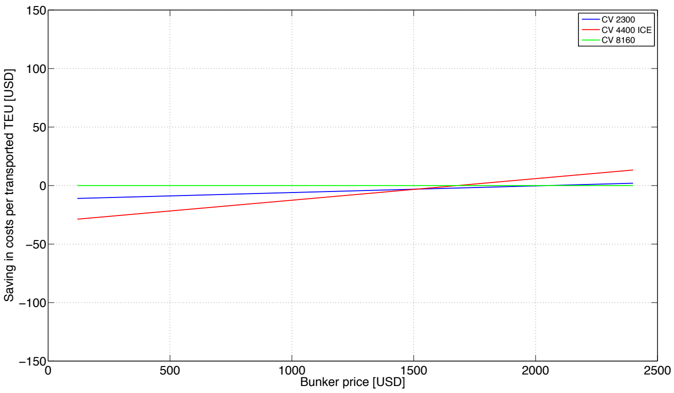
0 % ice scenario and 61 operational days along NSR



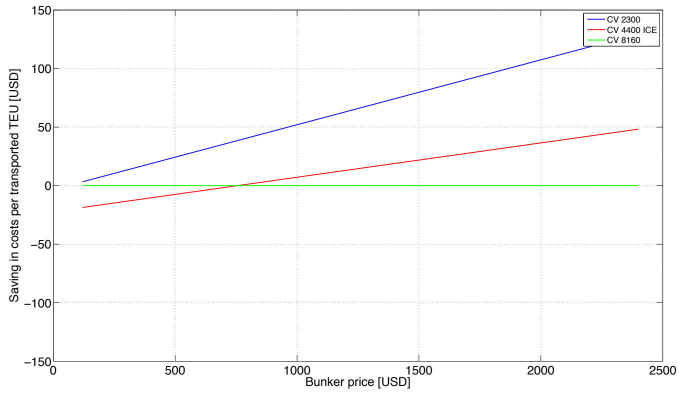
100 % ice scenario and 92 operational days along NSR



0 % ice scenario and 92operational days along NSR



100 % ice scenario and 122 operational days along NSR



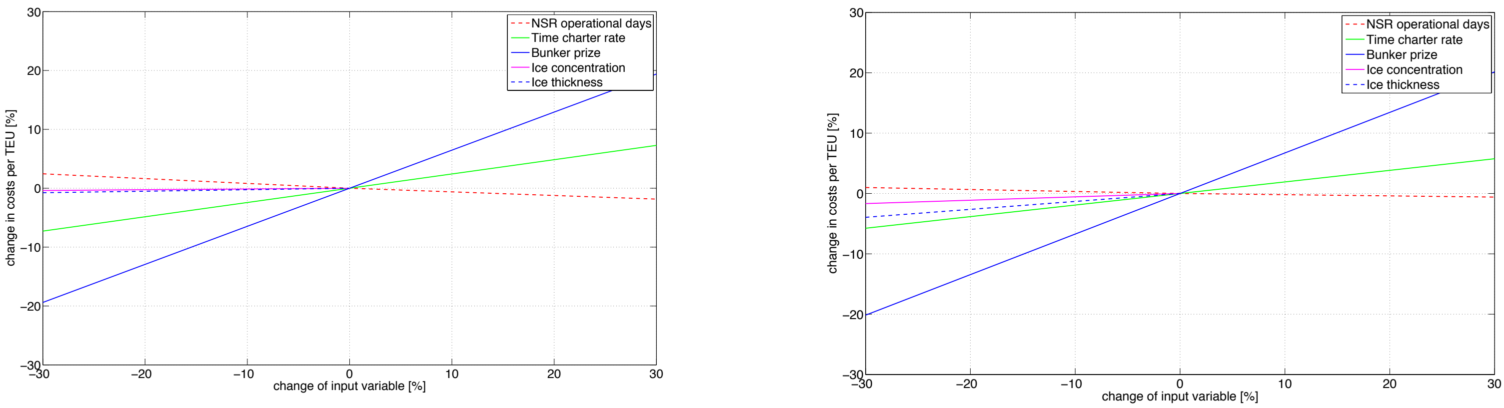
0 % ice scenario and 122 operational days along NSR

Fig. 30: Sensitivity plots for bunker price

Table 6: Analysis of sensitivity of bunker price in Fig. 30

100 % ice concentration, 61 operational days	0 % ice concentration, 61 operational days
Both vessels operating at the NSR need more fuel per transported TEU than the reference vessel and therefore are more expensive in transporting cargo. For this reason there are negative savings showed in the figure. The losses increase further with an increasing bunker price.	The CV 4400 ICE vessel makes negative savings that increase with a higher bunker price because of the higher fuel consumption. The CV 2300 makes losses at a low bunker price compared with the reference vessel but from a price of 400 USD/t upwards rising savings generated.
100 % ice concentration, 92 days operational days	0 % ice concentration, 92 operational days
As shown in Fig. 29 both vessels have minimal higher fuel consumption for this scenario than the reference vessel. This is leading to nearly constant losses at around -10 USD for CV 2300 and -30 USD for CV 4400 ICE respectively.	Although the fuel consumption is slightly lower for the CV 4400 ICE than the reference vessel, other route and vessel specific costs result in a loss from around -24 to -13 USD. The CV 2300 generates savings in cost from approximately 0 at the lower end of the examined bunker price up to 79 USD for the bunker price at the upper end of the scale.
100 % ice concentration, 122 days operational days	0 % ice concentration, 122 operational days
For this scenario both vessels make losses at a low bunker price, the CV 4400 ICE more than the CV 2300, but with increasing the bunker price the losses become less. For a relatively high bunker the CV 2300 overlaps with the reference vessel and the CV 4400 ICE makes even minimal savings of around 3 USD/t. The better performance in contrast to the smaller ship can be explained by the better performance of the ship in ice. Therefore it is able to utilize the NSR better.	The trend of the CV 2300 is the same as in the graph before with small savings at low bunker price and higher savings at a high bunker price. The CV 4400 ICE vessel makes losses for low bunker price and only after reaching a certain level of approximately 600 USD/t it generates savings compared with the reference vessel

For the analysis of the developed model and its application in the case study it is of interest which variables influence the final result to what degree. Therefore, a sensitivity study with a relative change of the input variables and their implication on the relative change of the output variable is carried out in Fig. 31. The main input variables are the operational days along the NSR, time charter rate, bunker price, ice concentration and ice thickness. The comparison between the model sensitivity for the vessel CV 4400 ICE and CV 2300 ICE shows that the trends are similar for both vessels, but there are also some important differences to mention. The CV 2300 is more sensitive to changes in the ice conditions than the CV 4400 ICE. The reason for this is, as already mentioned before, the ice class that enables the larger vessel to be more independent of the occurring ice conditions. For both vessels it is true that the ice thickness variation has more influence on the relative change in costs than the ice concentration. This can again be explained by the procedure the vessel is choosing the speed as already mentioned before. For ice concentration and ice thickness, the sensitivity is only investigated for a negative relative change. The reason for this is that the ice concentration and thickness in 2008, the year from which the ice data originates, were quite high. Considering that future predictions are in general expecting less ice, it is assumed that this is the maximum ice scenario for the model. Furthermore can be seen that the model is by far most sensitive for the bunker price. A 30 % increase in the bunker price results in a change of almost 20 % in the cost per transported TEU. The second largest influence is the time charter rate. For the CV 4400 ICE a 30 % change results in around 6 % magnitude. For the smaller vessel this values are a bit smaller. The third most important factor is the number of operational days. With increasing them from 61 to 122 days the cost per transported TEU can be reduced by 5 % for CV 4400 ICE and around 2 % for CV 2300. The vessel has next to its ice class also a higher service speed and therefore can utilize the NSR better. The reference vessel CV 8160 is independent of ice conditions and operational days along the NSR. Consequently, the result is not influenced by these variables at all. Only the time charter rate and the bunker price are of relevance. The sensitivity study of these variables for the reference vessel shows similar behavior as for the other ships.



CV 4400 ICE

CV 2300

Fig. 31: Model sensitivity for case study input parameters

To recapitulate, the sensitivity study gives a good insight in the relationship between input and output variables of the developed decision support tool. This helps to identify the input variables that cause most uncertainty in the output. Thus, ship operators have to try to reduce these first in order to increase the robustness of the transport system, but also to take a robust decision between the different vessel respectively route options. The definition for a robust decision is defined by Ullmann: 'A robust decision is the best possible choice, one found by eliminating all the uncertainty possible within available resources, and then choosing, with known and acceptable levels of satisfaction and risk.' (Ullman 2006). Nevertheless, not every uncertainty can be eliminated and, therefore, it is necessary to know the degree to which the output is subject to deviations. Only if the output is within a certain confidence interval the developed tool is able to support decisions in a reliable way. In Fig. 32 the model robustness for the CV4400 ICE vessel is shown. The SBDS-tool was run for a number of operational days of 61, 92 and 123 for eight times each. Based on the results the mean values have been calculated and are illustrated by the green line in the figure. The blue lines indicate the lower limit by connecting the minimum values and the upper limit by connecting the maximum values of the obtained results. The fluctuations in the results are then expected to be within the boundaries of this interval. In the case study example in Fig. 32 it can be seen that this interval is relatively small and therefore it is possible to speak of a robust transport system.

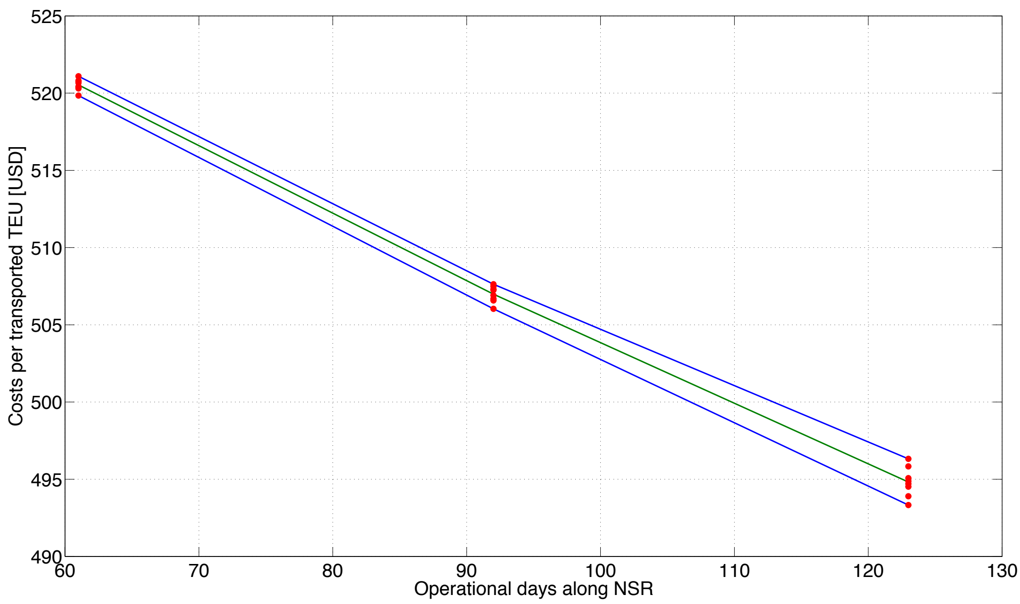


Fig. 32: Model robustness for CV4400 ICE vessel

In summary, one can say that under the assumptions made, the use of the NSR is not profitable when ice conditions prevail like in 2008. However, with the carried out sensitivity study it was shown that under certain circumstances the use of the NSR might be beneficial in the future. These include especially a diminishing sea ice in concentration and thickness and a sufficient long operational window to utilize the NSR. In addition, it was observed that a rising bunker price is reinforcing the trend of potential savings, but also losses. Contrary to expectations, no economy of scale effect influences the results. The smaller CV 2300 vessel is almost in all scenarios showing a better competitiveness than the CV 4400 ICE and even the much larger reference vessel with an almost four times as big capacity. However, the simulation is based on the assumption that the CV 2300, although it has no ice-class, can go under the same conditions as the CV 4400 ICE with ice class 1-C. The current Russian legislation (The Northern Sea Route Administration 2014) is putting here some constraints that are not considered in the case study. Furthermore, it is shown that under the considered uncertainties a robust transport system can be achieved.

Transit time results and sensitivity study

The simulation and case study is carried out in several steps. In the following explanations the results for the generation of day-specific transit time and fuel consumption are shown. This gives an important insight in the structure of the developed model.

In order to get the transit time for the route from Rotterdam to Yokohama, using the NSR, it is necessary to know the vessel speed for the different legs of the route. In Fig. 33 the computed vessel speed for the CV 4400 ICE depending on the ice conditions is shown. It is very apparent how much the ice conditions influence the vessel speed and consequently also the transit time. Furthermore, the figure illustrates how the vessel speed in ice is limited to a maximum speed of 10 knots. The procedure for calculating the vessel speed is described in detail in the flowchart in Fig. 15.

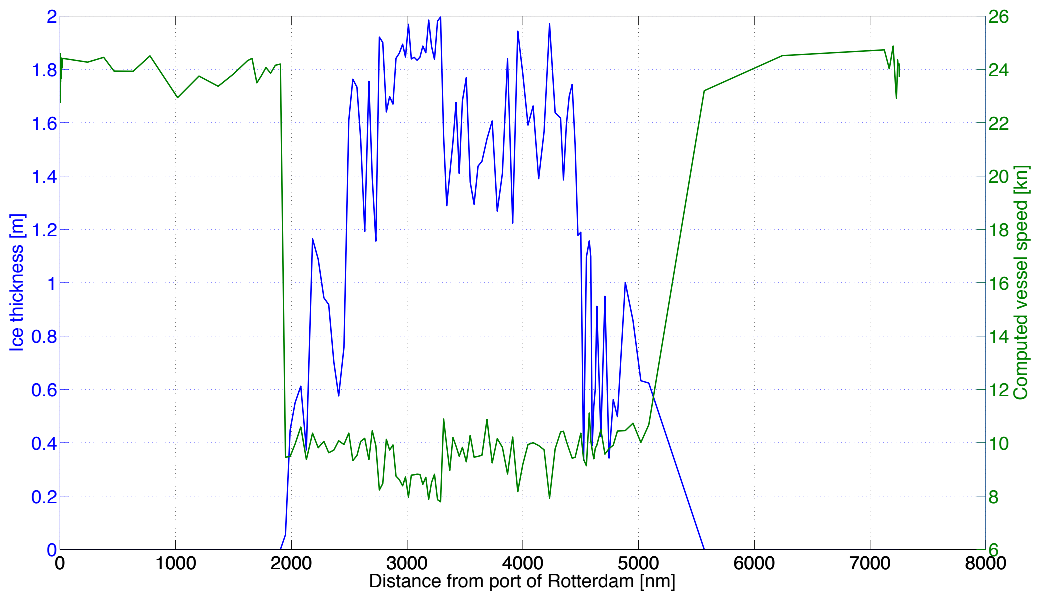


Fig. 33: Ice thickness and computed vessel speed for CV 4400 ICE along the route in March

With the knowledge of the vessel speed and the distances of the legs the transit time for every single day of the year can be calculated. The result of this procedure is shown in Fig. 34 and Fig. 35 where a sensitivity study for the transit times with a variation of the ice thickness and the ice concentration was done. In both figures a large difference in the transit time over the year is observable. This expected trend is corresponding with the sea ice extent in Fig. 25 and is explainable by the ice conditions that are lowest in the month August, September, October, and November and highest in March, April and May. In the carried out sensitivity study the ice thickness was reduced step by step to zero. The same was done for the ice concentration. With less ice the ship is able to go faster and therefore the transit time decreases significantly. Nevertheless, there are two tendencies in the figures that are worth to be mentioned. Firstly, in Fig. 34 it can be seen that with an ice thickness of 60 % of the original value the transit time doesn't sink further. The reason for this is that as long as there is ice, the ship does not go faster than 10 knots to protect the hull. In case the route is completely ice free a further reduction of the transit time is attained. Secondly, in Fig. 35 the transit time sinks above average between the 40 % to the 20 % ice concentration scenario. This is because of the defined rule that below an ice concentration of 30 % the ship can go at full open water speed in the ice-free part of the leg. In general the figures for the fuel consumption show the same trends as for the transit times. An exception in Fig. 36 is that for an ice thickness of 20 or 40 % the vessel needs less fuel than compared with an ice-free scenario. This is because of the previously mentioned "slow-steaming" effect. The ship is going slower than the h-v curve and the available propulsion power would allow and therefore fuel is saved compared when the ship is going with full open water speed and the full propulsion power is needed. Summarizing the above, it can be said that the reduction of ice thickness and concentration has a considerable impact on the transit times and on the fuel consumption for the NSR. Furthermore this would foster the economic feasibility of the NSR.

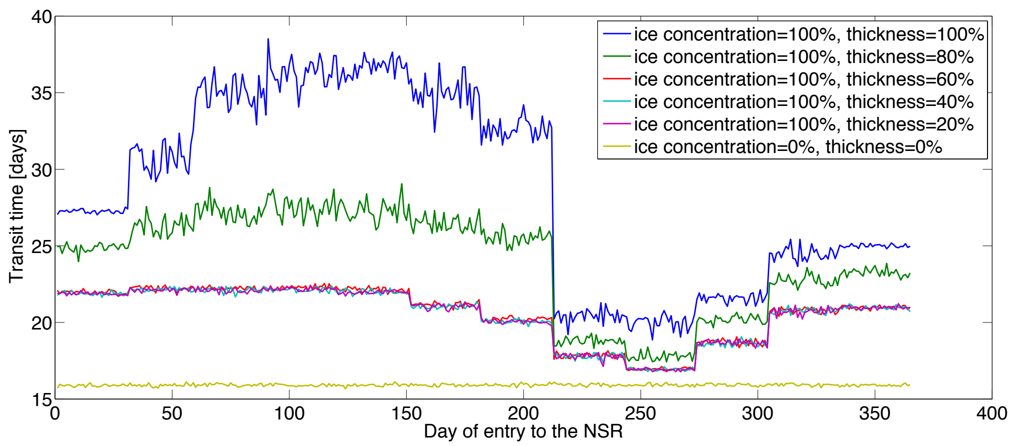


Fig. 34: Sensitivity analysis on CV 2300 transit times over a year for ice thickness variation

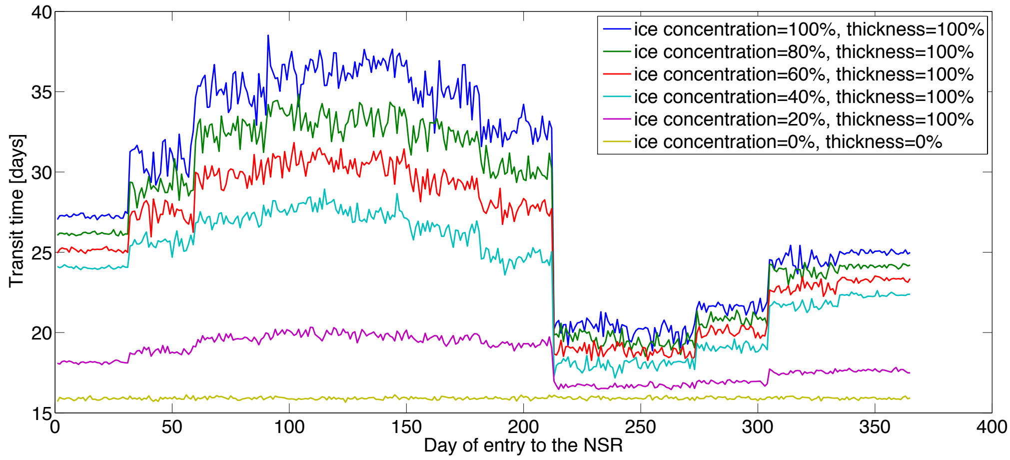


Fig. 35: Sensitivity analysis on CV 2300 transit times over a year for ice concentration variation

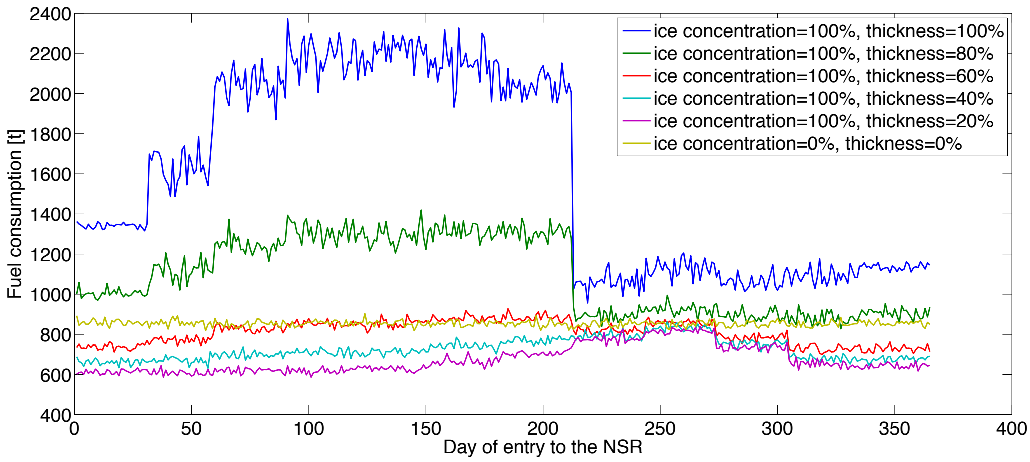


Fig. 36: Sensitivity analysis on CV 2300's day specific fuel consumption for the NSR over a year for ice thickness variation

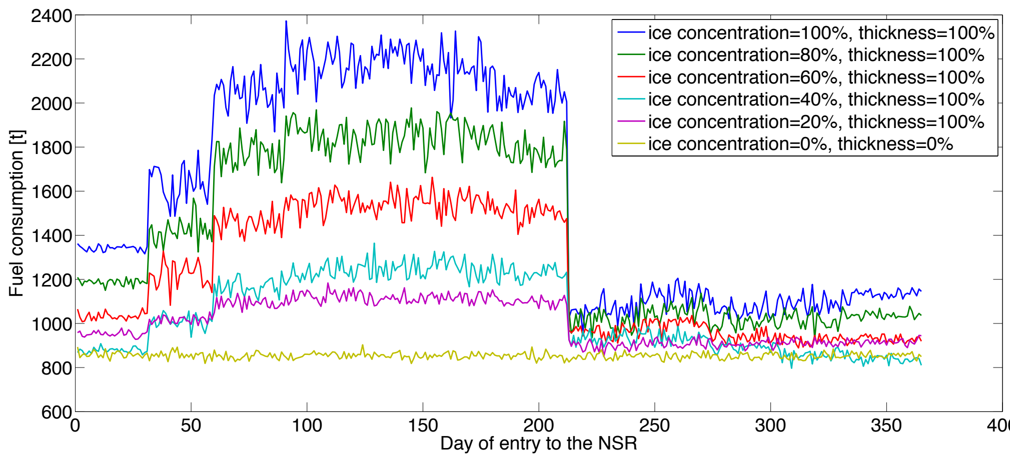


Fig. 37: Sensitivity analysis on CV 2300's day specific fuel consumption for the NSR a year for ice concentration variation

7 Discussion

The developed SBDS-tool is found to be capable of comparing different shipping routes and appears to be able to support ship operators and owners in their decision of selecting the most viable route for them. It can be analyzed in detail under what conditions the use of a route is profitable in comparison with an alternative route. These conditions can, for example, include the operational days of a route, route-specific ice conditions, chosen vessel specifications or waiting times. At the present state the SBDS-tool is designed for container shipping and therefore the cost per transported TEU cargo between two ports is compared. With this functionality enables the developed SBDS-tool to close an important gap in the present state of the art studies.

Moreover has the SBDS-tool the capability of integrating so-called combined routes. These are routes on which ships are operating along one route for a part of the year and along another route for the rest of the year. This feature is in particular of use for the implementation of arctic routes that are only utilizable partly of the year. Different vessel types can be integrated in the model and their open water performance and ice performance is calculated based on the existing equations in this field. In this way realistic transit times and fuel consumptions are obtained. In general, the acquired results seem, in particular for the main output, the cost of transporting cargo, reasonable for the specific input. Here must be said that the results of the SBDS-tool can be only as good as the quality of the input variables. Therefore, attention must be paid to the selection of used input data. The SBDS makes it possible to include a high number of input variables and analyze the influence of each on the final results. Moreover, sensitivity studies can show the relative model response to variation of the input data. Therefrom, it is possible to separate the relevant parameters of the less relevant. Furthermore, the SBDS-tool can deal with high uncertainties in input variables, an important capability for the evaluation of a new route, and provide information if a robust transport system can be obtained. The selected method of developing the tool on a simulation-based approach proves therefore as effective.

The SBDS-tool is built up modular and, therefore, relatively flexible to changes. For example, the module of the transit time and fuel consumption generation can easily be replaced if a different calculation method is preferred. Furthermore, it is easy to implement additional features such as the calculation of the pollution at a later point.

Some options are already built in such as the option that the ship is carrying different cargo loads east- and westbound or the option that the simulation is carried out for a fleet of ships. In addition, the simulation results in Simevents are very detailed and, thus, enable further analyses for the purpose of route optimization.

In addition, the SBDS-tool provides results from which economy of scale effects can be examined. This function is crucial for the decision which vessel is best to charter or invest in and seemed also quite absent in previous discussions.

For all these reasons, the developed SBDS-tool seems able to fill the identified gap in state of the art studies for supporting the ship operator in filtering out and examining the relevant information for its individual case and take future decisions based on this.

8 Summary

In this thesis, a SBDS-tool has been developed. It is able to compare different shipping routes and assess the economic feasibility from a ship operator's point of view. For the comparison of the different options the costs per transported TEU has been chosen as unit. In order to maximize the flexibility of the tool it is possible to implement different vessel types, combine routes and integrate input data with a high level of uncertainty like sea ice predictions, which is of particular interest for arctic routes. Furthermore, it can determine whether an economy of scale effect is present and whether a robust transport system can be achieved.

The decision support tool has been applied on a case study comparing the economic feasibility of the Northern Sea Route (NSR) with the Suez Canal Route (SCR) for container shipping between the ports of Rotterdam (NL) and Yokohama (JP). Three vessel types are compared. Two vessels have been operating during low-ice season at the NSR and the rest of the year at the SCR, the reference vessel is operating at the SCR on a year round basis. The results from the case study indicate that the NSR is not competitive with used ice data and assumptions made, but has the potential to become under certain conditions economic advantageous in the future. These include in particular a diminishing sea ice extent and longer operational days along the NSR.

9 Recommendations for future work

There are some points where the developed decision support tool could be improved and developed further in the future. Currently the open water resistance is calculated in MS Excel and then a curve is fitted in Matlab before it is implemented in the script for calculating the transit times and fuel consumption. Therefore it is recommended to include this calculation in the Matlab script in order to increase the user-friendliness of the tool. The same applies to the analysis and comparison of the costs that is presently also done in Excel. Moreover could be also the Matlab scripts for the generation of the h-v curve directly integrated in the transit time and fuel consumption script.

At the moment, the speed for the ice-free part of the route is only varying according to an assumed probability distribution and not directly related to the wave heights, ocean currents or winds. In order to make the ships performance as realistic as possible, it is suggested that also for the ice-free part of the route med-ocean data is used to calculate the speed and fuel consumption of the vessel.

Currently, the tool is underlying the assumption that the ship has always icebreaker support in ice and therefore only encounters brash ice resistance. Therefore it is recommended to expand this by level ice resistance in order to make it possible for the vessel to navigate independently along the route.

For the case study, it is suggested that the focus should be on the quality of the input data so that the results are better verified. Especially for the ice data predictions should be used up to date information. In addition, the costs could be broken down further to make the calculation of the transported costs per TEU more accurate.

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Appendix

The Appendix provides detailed information on the case study routes NSR and SCR. Furthermore, the developed Matlab Scripts and Excel calculations are presented. The following tables include the latitude and longitude coordinates of the route waypoints and the distance between them. For the NSR also the corresponding ice thicknesses and concentrations are listed for every month of the year. For each of them are two tables available, one for the minimum and one for the maximum value of measurement in this month. In the following table the route information for the SCR is presented.

Table 7: SCR route details

Latitude	Longitude	Waypoint	Distance [nm]	Cum. distance [nm]
51,9	4,5	1	0,3	0
51,9	4,5	2	0,5	1
51,9	4,4	3	0,5	1
51,9	4,4	4	0,4	2
51,9	4,4	5	0,4	2
51,9	4,4	6	0,3	2
51,9	4,4	7	0,2	3
51,9	4,4	8	0,2	3
51,9	4,4	9	0,4	3
51,9	4,4	10	0,5	4
51,9	4,4	11	0,2	4
51,9	4,4	12	0,3	4
51,9	4,4	13	0,6	5
51,9	4,3	14	0,4	5
51,9	4,3	15	0,4	6
51,9	4,3	16	0,3	6
51,9	4,3	17	0,4	6
51,9	4,3	18	2,5	9
51,9	4,2	19	1,0	10
51,9	4,2	20	1,2	11
51,9	4,2	21	3,2	14
52,0	4,1	22	3,3	18
52,0	4,0	23	6,4	24
52,0	3,9	24	102,3	126
51,1	1,6	25	11,9	138
50,9	1,4	26	35,3	173
50,6	0,7	27	130,0	304
49,8	-2,5	28	139,7	443
48,8	-5,7	29	377,1	820
43,2	-9,8	30	252,3	1073
39,0	-10,0	31	131,0	1204
36,9	-9,3	32	150,9	1354
36,0	-6,3	33	40,6	1395
36,0	-5,5	34	163,4	1558
36,4	-2,2	35	538,1	2096
37,6	9,0	36	60,8	2157
37,5	10,2	37	63,3	2221
37,3	11,5	38	151,0	2372
36,5	14,5	39	916,9	3288
31,7	32,0	40	28,4	3317
31,3	32,4	41	3,4	3320
31,3	32,4	42	4,9	3325
31,2	32,3	43	22,5	3348
30,8	32,3	44	6,0	3354
30,7	32,3	45	8,9	3362
30,6	32,3	46	3,0	3365
30,5	32,3	47	0,8	3366
30,5	32,3	48	3,5	3370
30,5	32,3	49	1,0	3371
30,4	32,4	50	5,1	3376
30,4	32,4	51	5,5	3381
30,3	32,4	52	3,5	3385
30,3	32,5	53	1,8	3387
30,2	32,5	54	3,5	3390
30,2	32,6	55	8,4	3399
30,1	32,6	56	4,8	3403
30,0	32,6	57	1,0	3404
30,0	32,6	58	1,1	3405
29,9	32,6	59	1,7	3407
29,9	32,6	60	17,7	3425
29,6	32,6	61	67,6	3492
28,6	33,1	62	41,9	3534
28,0	33,5	63	42,9	3577
27,5	34,1	64	446,2	4023
21,1	38,2	65	513,7	4537
13,6	42,6	66	5,4	4543
13,6	42,7	67	69,1	4612
12,6	43,3	68	9,4	4621
12,5	43,5	69	95,8	4717
12,0	45,0	70	545,8	5263
14,4	54,0	71	109,1	5372
13,8	55,8	72	1079,1	6451
7,7	73,0	73	466,8	6918
5,7	80,6	74	869,3	7787
6,2	95,1	75	153,4	7940
5,4	97,6	76	255,4	8196
2,8	101,0	77	59,2	8255
2,3	101,8	78	119,6	8374
1,2	103,5	79	17,5	8392
1,1	103,7	80	7,2	8399
1,2	103,9	81	14,6	8414
1,2	104,1	82	17,8	8432
1,3	104,4	83	8,8	8440
1,4	104,5	84	76,6	8517
2,6	105,0	85	379,2	8896
7,5	109,0	86	1089,4	9986
20,6	122,0	87	504,1	10490
26,3	128,7	88	726,7	11217
34,5	139,0	89	22,8	11239
34,8	139,3	90	27,4	11267
35,1	139,7	91	7,3	11274
35,2	139,8	92	2,9	11277
35,3	139,8	93	4,2	11281
35,3	139,7	94	7,7	11289
35,4	139,7	95	2,8	11292
35,5	139,7	96		

Table 8: Lower limits for ice concentrations along the NSR

Latitude	Longitude	Waypoint	Distance [nm]	Cum. distance [nm]	January	February	March	April	Mai	June	July	August	September	October	November	December
51,9	4,5	1	0,3	0	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,5	2	0,5	1	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	3	0,5	1	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	4	0,4	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	5	0,4	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	6	0,3	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	7	0,2	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	8	0,2	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	9	0,4	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	10	0,5	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	11	0,2	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	12	0,3	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	13	0,6	5	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	14	0,4	5	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	15	0,4	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	16	0,3	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	17	0,4	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	18	2,5	9	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	19	1,0	10	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	20	1,2	11	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	21	3,2	14	0	0	0	0	0	0	0	0	0	0	0	0
52,0	4,1	22	3,3	18	0	0	0	0	0	0	0	0	0	0	0	0
52,0	4,0	23	6,4	24	0	0	0	0	0	0	0	0	0	0	0	0
52,0	3,9	24	214,7	239	0	0	0	0	0	0	0	0	0	0	0	0
55,5	5,4	25	139,7	378	0	0	0	0	0	0	0	0	0	0	0	0
57,8	5,0	26	89,2	468	0	0	0	0	0	0	0	0	0	0	0	0
59,3	4,3	27	165,3	633	0	0	0	0	0	0	0	0	0	0	0	0
62,0	4,0	28	145,1	778	0	0	0	0	0	0	0	0	0	0	0	0
64,4	5,0	29	238,2	1016	0	0	0	0	0	0	0	0	0	0	0	0
68,0	9,0	30	184,8	1201	0	0	0	0	0	0	0	0	0	0	0	0
70,4	14,5	31	166,4	1367	0	0	0	0	0	0	0	0	0	0	0	0
72,0	21,5	32	127,5	1495	0	0	0	0	0	0	0	0	0	0	0	0
72,4	28,3	33	125,7	1621	0	0	0	0	0	0	0	0	0	0	0	0
72,0	35,0	34	39,2	1660	0	0	0	0	0	0	0	0	0	0	0	0
71,8	37,0	35	41,4	1701	0	0	0	0	0	0	0	0	0	0	0	0
71,6	39,1	36	39,9	1741	0	0	0	0	0	0	0	0	0	0	0	0
71,4	41,1	37	38,5	1780	0	0	0	0	0	0	0	0	0	0	0	0
71,2	43,0	38	40,7	1820	0	0	0	0	0	0	0	0	0	0	0	0
71,0	45,0	39	41,1	1862	0	0	0	0	0	0	0	0	0	0	0	0
70,8	47,0	40	43,4	1905	0	0	0	0	0	0	0	0	0	0	0	0
70,6	49,1	41	44,0	1949	0	0	0	0	0	0	0	0	0	0	0	0
70,3	51,1	42	40,5	1989	0	0	50	0	10	0	0	0	0	0	0	0
70,1	53,0	43	42,8	2032	0	0	80	80	20	0	0	0	0	0	0	0
69,9	55,0	44	49,0	2081	0	0	80	90	90	0	0	0	0	0	0	0
70,4	56,9	45	48,3	2129	90	80	90	90	90	90	0	0	0	0	0	0
70,9	58,8	46	52,9	2182	90	80	90	90	90	90	0	0	0	0	0	40
71,5	60,8	47	49,6	2232	90	80	90	90	90	90	0	0	0	0	0	40
72,0	62,9	48	48,8	2281	90	80	90	90	90	90	0	0	0	0	0	90
72,5	65,0	49	41,6	2322	90	90	90	90	90	90	0	0	0	0	0	90
72,9	66,9	50	44,7	2367	90	90	90	90	90	90	20	0	0	0	0	90
73,4	68,8	51	41,5	2408	90	90	90	90	90	90	60	0	0	0	0	90
73,8	70,8	52	45,8	2454	90	90	90	90	90	90	60	0	0	0	0	90
74,3	72,9	53	41,4	2496	90	90	90	90	90	90	80	0	0	0	0	90
74,7	75,0	54	34,8	2531	90	90	90	90	90	90	80	0	0	0	90	90
75,0	76,9	55	35,7	2566	90	90	90	90	90	90	80	0	0	0	90	90
75,3	78,9	56	32,6	2599	90	90	90	90	90	90	80	0	0	0	90	90
75,5	80,9	57	34,8	2634	90	90	90	90	90	90	80	0	0	0	90	90
75,8	82,9	58	35,5	2669	90	90	90	90	90	90	80	0	0	0	90	90
76,1	85,0	59	29,7	2699	90	90	90	90	90	90	80	0	0	0	90	90
76,3	86,9	60	30,7	2729	90	90	90	90	90	90	80	0	0	0	90	90
76,5	88,9	61	30,3	2760	90	90	90	100	90	90	80	0	0	20	90	90
76,7	90,9	62	29,9	2790	90	90	90	100	100	100	90	0	0	20	90	90
76,9	92,9	63	30,8	2821	90	90	90	100	100	100	90	0	40	20	90	90
77,1	95,0	64	28,0	2848	90	90	100	100	100	100	90	50	0	60	90	90
77,3	96,9	65	28,8	2877	90	90	100	100	100	100	90	50	0	80	90	90
77,5	98,9	66	26,6	2904	90	90	100	100	100	100	90	50	70	80	90	90
77,6	100,9	67	28,3	2932	90	90	100	100	100	100	90	50	0	80	90	90
77,8	102,9	68	29,0	2961	90	90	100	100	100	100	90	50	0	80	90	90
78,0	105,0	69	25,0	2986	90	90	100	90	100	100	90	0	0	80	90	90
78,0	107,0	70	25,0	3011	90	90	90	90	90	90	90	0	0	80	90	90
78,0	109,0	71	25,0	3036	90	90	90	90	90	90	90	0	0	80	90	90
78,0	111,0	72	25,0	3061	90	90	90	90	90	90	90	0	0	80	90	90
78,0	113,0	73	25,0	3086	90	90	90	90	90	90	90	0	100	80	90	90

Table continues on the next page ...

Latitude	Longitude	Waypoint	Distance [nm]	Cum. distance [nm]	January	February	March	April	Mai	June	July	August	September	October	November	December
78,0	115,0	74	25,0	3111	90	90	90	90	90	90	90	0	100	80	90	90
78,0	117,0	75	25,0	3136	90	90	90	90	90	90	90	0	80	80	90	90
78,0	119,0	76	25,0	3161	90	90	90	90	90	90	90	0	80	80	90	90
78,0	121,0	77	25,0	3186	90	90	90	90	90	90	90	0	80	90	90	90
78,0	123,0	78	25,0	3211	90	90	90	90	90	90	90	0	90	90	90	90
78,0	125,0	79	25,8	3237	90	90	90	90	90	90	90	0	90	90	90	90
77,9	127,0	80	26,0	3263	90	90	90	90	90	90	90	0	90	90	90	90
77,8	129,0	81	26,2	3289	90	90	90	90	90	90	90	0	90	90	90	90
77,7	131,0	82	26,4	3315	90	90	90	90	90	90	90	0	90	90	90	90
77,6	133,0	83	26,6	3342	90	90	90	90	90	90	90	0	90	90	90	90
77,5	135,0	84	26,8	3368	90	90	90	90	90	90	90	0	90	90	90	90
77,4	137,0	85	27,0	3395	90	90	90	90	90	90	90	0	0	80	90	90
77,3	139,0	86	27,2	3423	90	90	90	90	90	90	90	0	0	80	90	90
77,2	141,0	87	27,4	3450	90	90	90	90	90	90	90	0	0	0	90	90
77,1	143,0	88	27,6	3478	90	90	90	90	90	90	90	0	0	0	90	90
77,0	145,0	89	33,9	3511	90	90	90	90	90	90	90	0	0	0	90	90
76,7	147,1	90	33,2	3545	90	90	90	90	90	90	90	0	0	0	90	90
76,4	149,1	91	33,7	3578	90	90	90	90	90	90	90	0	0	0	90	90
76,1	151,1	92	34,3	3613	90	90	90	90	90	90	90	0	0	0	90	90
75,8	153,1	93	33,5	3646	90	90	90	90	90	90	90	0	0	0	90	90
75,5	155,0	94	43,9	3690	90	90	90	90	90	90	90	0	0	0	90	90
75,0	157,1	95	44,7	3735	90	90	90	90	90	90	90	0	0	0	90	90
74,5	159,2	96	44,3	3779	90	90	90	90	90	90	90	0	0	0	90	90
74,0	161,2	97	43,8	3823	90	90	90	90	90	90	90	0	0	0	90	90
73,5	163,1	98	44,5	3868	90	90	90	90	90	90	90	0	0	0	90	90
73,0	165,0	99	44,3	3912	90	90	90	90	90	90	90	50	0	90	90	90
72,6	167,1	100	43,5	3955	90	90	90	90	90	90	90	0	0	90	90	90
72,2	169,1	101	44,2	4000	90	90	90	90	90	90	90	0	0	0	90	90
71,8	171,1	102	44,9	4044	90	90	90	90	90	90	50	0	0	0	90	90
71,4	173,1	103	43,9	4088	90	90	90	90	90	90	50	0	0	0	90	90
71,0	175,0	104	47,9	4136	90	90	90	90	90	90	70	0	90	0	90	90
70,6	177,1	105	46,9	4183	90	90	90	90	90	90	70	0	90	0	90	90
70,2	179,1	106	47,6	4231	90	90	90	90	90	90	70	0	90	0	90	90
69,8	-178,9	107	48,3	4279	90	90	90	90	90	90	0	0	0	0	80	90
69,4	-176,9	108	47,1	4326	90	90	90	90	90	90	0	0	0	0	30	90
69,0	-175,0	109	24,7	4351	90	90	90	90	90	50	0	0	0	0	0	90
68,8	-174,0	110	24,9	4376	90	90	90	90	90	50	0	0	0	0	0	90
68,6	-173,0	111	25,1	4401	90	90	90	90	90	50	0	0	0	0	0	90
68,4	-172,0	112	25,2	4426	90	90	90	90	90	50	0	0	0	0	0	90
68,2	-171,0	113	25,4	4451	90	90	90	90	90	40	0	0	0	0	0	90
68,0	-170,0	114	24,4	4476	90	90	90	90	90	40	0	0	0	0	0	90
67,6	-169,8	115	24,5	4500	90	90	90	90	70	40	0	0	0	0	0	90
67,2	-169,6	116	24,5	4525	90	90	90	90	70	0	0	0	0	0	0	90
66,8	-169,4	117	24,5	4549	90	90	90	90	60	0	0	0	0	0	0	90
66,4	-169,2	118	24,5	4574	90	90	90	90	60	0	0	0	0	0	0	90
66,0	-169,0	119	13,0	4587	90	90	90	90	60	0	0	0	0	0	0	90
65,8	-169,2	120	13,0	4600	90	90	90	90	50	0	0	0	0	0	0	90
65,6	-169,4	121	13,0	4613	90	90	90	90	50	0	0	0	0	0	0	90
65,4	-169,6	122	13,0	4626	90	90	90	90	50	0	0	0	0	0	0	50
65,2	-169,8	123	13,0	4639	90	90	90	90	60	0	0	0	0	0	0	50
65,0	-170,0	124	35,1	4674	90	90	90	90	60	0	0	0	0	0	0	0
64,6	-171,0	125	35,4	4709	90	90	90	90	60	0	0	0	0	0	0	0
64,2	-172,0	126	35,6	4745	90	90	90	90	60	0	0	0	0	0	0	0
63,8	-173,0	127	35,9	4781	90	90	90	90	80	0	0	0	0	0	0	0
63,4	-174,0	128	36,2	4817	90	90	90	90	80	0	0	0	0	0	0	0
63,0	-175,0	129	68,1	4885	90	90	90	90	60	0	0	0	0	0	0	0
62,4	-177,1	130	66,7	4952	90	90	0	90	0	0	0	0	0	0	0	0
61,8	-179,1	131	67,7	5020	90	90	0	90	0	0	0	0	0	0	0	0
61,2	178,9	132	68,6	5088	90	90	0	80	0	0	0	0	0	0	0	0
60,6	176,9	133	479,1	5567	0	0	0	0	0	0	0	0	0	0	0	0
55,7	165,0	134	674,8	6242	0	0	0	0	0	0	0	0	0	0	0	0
46,8	153,9	135	881,0	7123	0	0	0	0	0	0	0	0	0	0	0	0
35,7	141,2	136	43,6	7167	0	0	0	0	0	0	0	0	0	0	0	0
35,1	140,6	137	33,5	7200	0	0	0	0	0	0	0	0	0	0	0	0
34,8	140,0	138	10,8	7211	0	0	0	0	0	0	0	0	0	0	0	0
34,8	139,8	139	8,9	7220	0	0	0	0	0	0	0	0	0	0	0	0
35,0	139,7	140	8,1	7228	0	0	0	0	0	0	0	0	0	0	0	0
35,1	139,7	141	7,3	7235	0	0	0	0	0	0	0	0	0	0	0	0
35,2	139,8	142	2,9	7238	0	0	0	0	0	0	0	0	0	0	0	0
35,3	139,8	143	4,2	7242	0	0	0	0	0	0	0	0	0	0	0	0
35,3	139,7	144	7,7	7250	0	0	0	0	0	0	0	0	0	0	0	0
35,4	139,7	145	2,8	**7253**	0	0	0	0	0	0	0	0	0	0	0	0
35,5	139,7															

Table 9: Upper limits for ice concentrations along the NSR

Latitude	Longitude	Waypoint	Distance [nm]	Cum. distance [nm]	January	February	March	April	Mai	June	July	August	September	October	November	December
51,9	4,5	1	0,3	0	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,5	2	0,5	1	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	3	0,5	1	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	4	0,4	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	5	0,4	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	6	0,3	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	7	0,2	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	8	0,2	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	9	0,4	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	10	0,5	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	11	0,2	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	12	0,3	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	13	0,6	5	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	14	0,4	5	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	15	0,4	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	16	0,3	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	17	0,4	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	18	2,5	9	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	19	1,0	10	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	20	1,2	11	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	21	3,2	14	0	0	0	0	0	0	0	0	0	0	0	0
52,0	4,1	22	3,3	18	0	0	0	0	0	0	0	0	0	0	0	0
52,0	4,0	23	6,4	24	0	0	0	0	0	0	0	0	0	0	0	0
52,0	3,9	24	214,7	239	0	0	0	0	0	0	0	0	0	0	0	0
55,5	5,4	25	139,7	378	0	0	0	0	0	0	0	0	0	0	0	0
57,8	5,0	26	89,2	468	0	0	0	0	0	0	0	0	0	0	0	0
59,3	4,3	27	165,3	633	0	0	0	0	0	0	0	0	0	0	0	0
62,0	4,0	28	145,1	778	0	0	0	0	0	0	0	0	0	0	0	0
64,4	5,0	29	238,2	1016	0	0	0	0	0	0	0	0	0	0	0	0
68,0	9,0	30	184,8	1201	0	0	0	0	0	0	0	0	0	0	0	0
70,4	14,5	31	166,4	1367	0	0	0	0	0	0	0	0	0	0	0	0
72,0	21,5	32	127,5	1495	0	0	0	0	0	0	0	0	0	0	0	0
72,4	28,3	33	125,7	1621	0	0	0	0	0	0	0	0	0	0	0	0
72,0	35,0	34	39,2	1660	0	0	0	0	0	0	0	0	0	0	0	0
71,8	37,0	35	41,4	1701	0	0	0	0	0	0	0	0	0	0	0	0
71,6	39,1	36	39,9	1741	0	0	0	0	0	0	0	0	0	0	0	0
71,4	41,1	37	38,5	1780	0	0	0	0	0	0	0	0	0	0	0	0
71,2	43,0	38	40,7	1820	0	0	0	0	0	0	0	0	0	0	0	0
71,0	45,0	39	41,1	1862	0	0	0	0	0	0	0	0	0	0	0	0
70,8	47,0	40	43,4	1905	0	0	0	0	0	0	0	0	0	0	0	0
70,6	49,1	41	44,0	1949	0	100	100	70	100	0	0	0	0	0	0	0
70,3	51,1	42	40,5	1989	0	100	100	70	100	0	0	0	0	0	0	0
70,1	53,0	43	42,8	2032	0	100	100	100	100	0	0	0	0	0	0	0
69,9	55,0	44	49,0	2081	0	100	100	100	100	0	0	0	0	0	0	0
70,4	56,9	45	48,3	2129	100	100	100	100	100	100	100	0	0	0	100	60
70,9	58,8	46	52,9	2182	100	100	100	100	100	100	100	0	0	0	100	80
71,5	60,8	47	49,6	2232	100	100	100	100	100	100	100	0	0	0	100	80
72,0	62,9	48	48,8	2281	100	100	100	100	100	100	100	0	0	0	100	100
72,5	65,0	49	41,6	2322	100	100	100	100	100	100	100	0	0	0	100	100
72,9	66,9	50	44,7	2367	100	100	100	100	100	100	100	0	0	0	100	100
73,4	68,8	51	41,5	2408	100	100	100	100	100	100	100	0	0	0	100	100
73,8	70,8	52	45,8	2454	100	100	100	100	100	100	100	0	0	100	100	100
74,3	72,9	53	41,4	2496	100	100	100	100	100	100	100	0	0	100	100	100
74,7	75,0	54	34,8	2531	100	100	100	100	100	100	100	0	0	100	100	100
75,0	76,9	55	35,7	2566	100	100	100	100	100	100	100	0	0	100	100	100
75,3	78,9	56	32,6	2599	100	100	100	100	100	100	100	0	0	0	100	100
75,5	80,9	57	34,8	2634	100	100	100	100	100	100	100	0	0	70	100	100
75,8	82,9	58	35,5	2669	100	100	100	100	100	100	100	0	0	70	100	100
76,1	85,0	59	29,7	2699	100	100	100	100	100	100	100	0	0	70	100	100
76,3	86,9	60	30,7	2729	100	100	100	100	100	100	100	30	0	100	100	100
76,5	88,9	61	30,3	2760	100	100	100	100	100	100	100	100	0	100	100	100
76,7	90,9	62	29,9	2790	100	100	100	100	100	100	100	100	0	100	100	100
76,9	92,9	63	30,8	2821	100	100	100	100	100	100	100	100	60	100	100	100
77,1	95,0	64	28,0	2848	100	100	100	100	100	100	100	100	0	100	100	100
77,3	96,9	65	28,8	2877	100	100	100	100	100	100	100	100	0	100	100	100
77,5	98,9	66	26,6	2904	100	100	100	100	100	100	100	100	90	100	100	100
77,6	100,9	67	28,3	2932	100	100	100	100	100	100	100	100	10	100	100	100
77,8	102,9	68	29,0	2961	100	100	100	100	100	100	100	100	10	100	100	100
78,0	105,0	69	25,0	2986	100	100	100	100	100	100	100	100	10	100	100	100
78,0	107,0	70	25,0	3011	100	100	100	100	100	100	100	70	0	100	100	100
78,0	109,0	71	25,0	3036	100	100	100	100	100	100	100	70	0	100	100	100
78,0	111,0	72	25,0	3061	100	100	100	100	100	100	100	70	0	100	100	100
78,0	113,0	73	25,0	3086	100	100	100	100	100	100	100	0	100	100	100	100

Table continues on the next page ...

Latitude	Longitude	Waypoint	Distance [nm]	Cum. distance [nm]	January	February	March	April	Mai	June	July	August	September	October	November	December
78,0	115,0	74	25,0	3111	100	100	100	100	100	100	100	0	100	100	100	100
78,0	117,0	75	25,0	3136	100	100	100	100	100	100	100	0	100	100	100	100
78,0	119,0	76	25,0	3161	100	100	100	100	100	100	100	100	100	100	100	100
78,0	121,0	77	25,0	3186	100	100	100	100	100	100	100	100	100	100	100	100
78,0	123,0	78	25,0	3211	100	100	100	100	100	100	100	100	100	100	100	100
78,0	125,0	79	25,8	3237	100	100	100	100	100	100	100	100	100	100	100	100
77,9	127,0	80	26,0	3263	100	100	100	100	100	100	100	100	100	100	100	100
77,8	129,0	81	26,2	3289	100	100	100	100	100	100	100	90	100	100	100	100
77,7	131,0	82	26,4	3315	100	100	100	100	100	100	100	100	100	100	100	100
77,6	133,0	83	26,6	3342	100	100	100	100	100	100	100	100	100	100	100	100
77,5	135,0	84	26,8	3368	100	100	100	100	100	100	100	30	100	100	100	100
77,4	137,0	85	27,0	3395	100	100	100	100	100	100	100	100	0	100	100	100
77,3	139,0	86	27,2	3423	100	100	100	100	100	100	100	100	0	100	100	100
77,2	141,0	87	27,4	3450	100	100	100	100	100	100	100	100	0	100	100	100
77,1	143,0	88	27,6	3478	100	100	100	100	100	100	100	100	0	100	100	100
77,0	145,0	89	33,9	3511	100	100	100	100	100	100	100	10	0	100	100	100
76,7	147,1	90	33,2	3545	100	100	100	100	100	100	100	10	0	100	100	100
76,4	149,1	91	33,7	3578	100	100	100	100	100	100	100	10	0	100	100	100
76,1	151,1	92	34,3	3613	100	100	100	100	100	100	100	90	0	100	100	100
75,8	153,1	93	33,5	3646	100	100	100	100	100	100	100	90	0	100	100	100
75,5	155,0	94	43,9	3690	100	100	100	100	100	100	100	90	0	100	100	100
75,0	157,1	95	44,7	3735	100	100	100	100	100	100	100	100	0	100	100	100
74,5	159,2	96	44,3	3779	100	100	100	100	100	100	100	100	0	100	100	100
74,0	161,2	97	43,8	3823	100	100	100	100	100	100	100	100	0	100	100	100
73,5	163,1	98	44,5	3868	100	100	100	100	100	100	100	100	0	100	100	100
73,0	165,0	99	44,3	3912	100	100	100	100	100	100	100	100	0	100	100	100
72,6	167,1	100	43,5	3955	100	100	100	100	100	100	100	100	0	100	100	100
72,2	169,1	101	44,2	4000	100	100	100	100	100	100	100	100	0	100	100	100
71,8	171,1	102	44,9	4044	100	100	100	100	100	100	100	90	0	100	100	100
71,4	173,1	103	43,9	4088	100	100	100	100	100	100	100	90	0	0	100	100
71,0	175,0	104	47,9	4136	100	100	100	100	100	100	100	90	100	0	100	100
70,6	177,1	105	46,9	4183	100	100	100	100	100	100	100	40	100	0	100	100
70,2	179,1	106	47,6	4231	100	100	100	100	100	100	100	0	100	0	100	100
69,8	-178,9	107	48,3	4279	100	100	100	100	100	100	0	0	0	0	100	100
69,4	-176,9	108	47,1	4326	100	100	100	100	100	100	0	0	0	0	100	100
69,0	-175,0	109	24,7	4351	100	100	100	100	100	100	0	0	0	0	100	100
68,8	-174,0	110	24,9	4376	100	100	100	100	100	100	0	0	0	0	100	100
68,6	-173,0	111	25,1	4401	100	100	100	100	100	100	0	0	0	0	100	100
68,4	-172,0	112	25,2	4426	100	100	100	100	100	100	0	0	0	0	100	100
68,2	-171,0	113	25,4	4451	100	100	100	100	100	70	0	0	0	0	100	100
68,0	-170,0	114	24,4	4476	100	100	100	100	100	70	0	0	0	0	100	100
67,6	-169,8	115	24,5	4500	100	100	100	100	100	70	0	0	0	0	100	100
67,2	-169,6	116	24,5	4525	100	100	100	100	100	70	0	0	0	0	100	100
66,8	-169,4	117	24,5	4549	100	100	100	100	90	70	0	0	0	0	100	100
66,4	-169,2	118	24,5	4574	100	100	100	100	90	70	0	0	0	0	100	100
66,0	-169,0	119	13,0	4587	100	100	100	100	90	70	0	0	0	0	100	100
65,8	-169,2	120	13,0	4600	100	100	100	100	90	70	0	0	0	0	100	100
65,6	-169,4	121	13,0	4613	100	100	100	100	80	70	0	0	0	0	100	100
65,4	-169,6	122	13,0	4626	100	100	100	100	80	10	0	0	0	0	70	100
65,2	-169,8	123	13,0	4639	100	100	100	100	80	10	0	0	0	0	70	100
65,0	-170,0	124	35,1	4674	100	100	100	100	90	10	0	0	0	0	70	0
64,6	-171,0	125	35,4	4709	100	100	100	100	90	10	0	0	0	0	70	0
64,2	-172,0	126	35,6	4745	100	100	100	100	100	10	0	0	0	0	70	0
63,8	-173,0	127	35,9	4781	100	100	100	100	100	70	0	0	0	0	0	0
63,4	-174,0	128	36,2	4817	100	100	100	100	100	70	0	0	0	0	0	0
63,0	-175,0	129	68,1	4885	100	100	100	100	100	70	0	0	0	0	0	0
62,4	-177,1	130	66,7	4952	100	100	100	100	100	0	0	0	0	0	0	0
61,8	-179,1	131	67,7	5020	100	100	100	100	90	0	0	0	0	0	0	0
61,2	178,9	132	68,6	5088	100	100	100	100	0	0	0	0	0	0	0	0
60,6	176,9	133	479,1	5567	0	0	0	0	0	0	0	0	0	0	0	0
55,7	165,0	134	674,8	6242	0	0	0	0	0	0	0	0	0	0	0	0
46,8	153,9	135	881,0	7123	0	0	0	0	0	0	0	0	0	0	0	0
35,7	141,2	136	43,6	7167	0	0	0	0	0	0	0	0	0	0	0	0
35,1	140,6	137	33,5	7200	0	0	0	0	0	0	0	0	0	0	0	0
34,8	140,0	138	10,8	7211	0	0	0	0	0	0	0	0	0	0	0	0
34,8	139,8	139	8,9	7220	0	0	0	0	0	0	0	0	0	0	0	0
35,0	139,7	140	8,1	7228	0	0	0	0	0	0	0	0	0	0	0	0
35,1	139,7	141	7,3	7235	0	0	0	0	0	0	0	0	0	0	0	0
35,2	139,8	142	2,9	7238	0	0	0	0	0	0	0	0	0	0	0	0
35,3	139,8	143	4,2	7242	0	0	0	0	0	0	0	0	0	0	0	0
35,3	139,7	144	7,7	7250	0	0	0	0	0	0	0	0	0	0	0	0
35,4	139,7	145	2,8	**7253**	0	0	0	0	0	0	0	0	0	0	0	0
35,5	139,7															

Table 10: Lower limits for ice thicknesses along the NSR

Latitude	Longitude	Waypoint	Distance [nm]	cum. Distance [nm]	January	February	March	April	Mai	June	July	August	September	October	November	December
51,9	4,5	1	0,3	0	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,5	2	0,5	1	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	3	0,5	1	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	4	0,4	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	5	0,4	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	6	0,3	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	7	0,2	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	8	0,2	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	9	0,4	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	10	0,5	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	11	0,2	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	12	0,3	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	13	0,6	5	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	14	0,4	5	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	15	0,4	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	16	0,3	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	17	0,4	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	18	2,5	9	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	19	1,0	10	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	20	1,2	11	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	21	3,2	14	0	0	0	0	0	0	0	0	0	0	0	0
52,0	4,1	22	3,3	18	0	0	0	0	0	0	0	0	0	0	0	0
52,0	4,0	23	6,4	24	0	0	0	0	0	0	0	0	0	0	0	0
52,0	3,9	24	214,7	239	0	0	0	0	0	0	0	0	0	0	0	0
55,5	5,4	25	139,7	378	0	0	0	0	0	0	0	0	0	0	0	0
57,8	5,0	26	89,2	468	0	0	0	0	0	0	0	0	0	0	0	0
59,3	4,3	27	165,3	633	0	0	0	0	0	0	0	0	0	0	0	0
62,0	4,0	28	145,1	778	0	0	0	0	0	0	0	0	0	0	0	0
64,4	5,0	29	238,2	1016	0	0	0	0	0	0	0	0	0	0	0	0
68,0	9,0	30	184,8	1201	0	0	0	0	0	0	0	0	0	0	0	0
70,4	14,5	31	166,4	1367	0	0	0	0	0	0	0	0	0	0	0	0
72,0	21,5	32	127,5	1495	0	0	0	0	0	0	0	0	0	0	0	0
72,4	28,3	33	125,7	1621	0	0	0	0	0	0	0	0	0	0	0	0
72,0	35,0	34	39,2	1660	0	0	0	0	0	0	0	0	0	0	0	0
71,8	37,0	35	41,4	1701	0	0	0	0	0	0	0	0	0	0	0	0
71,6	39,1	36	39,9	1741	0	0	0	0	0	0	0	0	0	0	0	0
71,4	41,1	37	38,5	1780	0	0	0	0	0	0	0	0	0	0	0	0
71,2	43,0	38	40,7	1820	0	0	0	0	0	0	0	0	0	0	0	0
71,0	45,0	39	41,1	1862	0	0	0	0	0	0	0	0	0	0	0	0
70,8	47,0	40	43,4	1905	0	0	0	0	0	0	0	0	0	0	0	0
70,6	49,1	41	44,0	1949	0	0	0	0	0	0	0	0	0	0	0	0
70,3	51,1	42	40,5	1989	0	0	30	0	30	0	0	0	0	0	0	0
70,1	53,0	43	42,8	2032	0	0	30	30	30	0	0	0	0	0	0	0
69,9	55,0	44	49,0	2081	0	0	30	30	30	0	0	0	0	0	0	0
70,4	56,9	45	48,3	2129	10	10	30	70	30	70	0	0	0	0	0	0
70,9	58,8	46	52,9	2182	30	30	70	70	70	70	0	0	0	0	0	10
71,5	60,8	47	49,6	2232	30	30	70	70	70	70	0	0	0	0	0	10
72,0	62,9	48	48,8	2281	30	30	70	70	70	70	0	0	0	0	0	30
72,5	65,0	49	41,6	2322	30	30	70	70	70	70	0	0	0	0	0	30
72,9	66,9	50	44,7	2367	30	30	30	70	70	70	70	0	0	0	0	30
73,4	68,8	51	41,5	2408	30	30	30	70	70	120	70	0	0	0	0	30
73,8	70,8	52	45,8	2454	30	70	30	120	120	120	120	0	0	0	0	30
74,3	72,9	53	41,4	2496	30	70	120	120	120	120	120	0	0	0	0	30
74,7	75,0	54	34,8	2531	30	70	70	120	120	120	120	0	0	0	10	30
75,0	76,9	55	35,7	2566	30	70	70	120	120	120	120	0	0	0	10	30
75,3	78,9	56	32,6	2599	70	70	70	120	120	120	120	0	0	0	10	30
75,5	80,9	57	34,8	2634	70	70	70	120	120	120	120	0	0	0	10	30
75,8	82,9	58	35,5	2669	70	70	70	120	120	120	120	0	0	0	10	30
76,1	85,0	59	29,7	2699	70	70	70	120	120	120	120	0	0	0	10	30
76,3	86,9	60	30,7	2729	70	70	70	120	120	120	120	0	0	0	10	30
76,5	88,9	61	30,3	2760	70	70	70	120	120	120	120	0	0	10	10	30
76,7	90,9	62	29,9	2790	70	70	120	120	120	120	120	0	0	10	10	30
76,9	92,9	63	30,8	2821	200	200	120	120	120	120	120	0	120	10	10	30
77,1	95,0	64	28,0	2848	200	200	120	120	120	120	120	200	0	10	200	30
77,3	96,9	65	28,8	2877	200	200	120	120	120	120	120	200	0	10	200	30
77,5	98,9	66	26,6	2904	200	200	200	120	120	120	200	200	120	10	200	30
77,6	100,9	67	28,3	2932	200	200	200	200	200	120	200	200	120	10	200	30
77,8	102,9	68	29,0	2961	200	200	200	200	200	200	200	200	120	10	10	30
78,0	105,0	69	25,0	2986	200	200	200	200	200	200	200	0	120	10	10	200
78,0	107,0	70	25,0	3011	200	200	200	200	120	200	200	0	0	10	10	200
78,0	109,0	71	25,0	3036	200	200	200	120	120	200	200	0	0	10	10	200
78,0	111,0	72	25,0	3061	200	200	200	120	120	200	200	0	0	10	10	200
78,0	113,0	73	25,0	3086	200	200	200	120	120	120	200	0	120	10	10	200

Table continues on the next page ...

Latitude	Longitude	Waypoint	Distance [nm]	Cum. distance [nm]	January	February	March	April	Mai	June	July	August	September	October	November	December
78,0	115,0	74	25,0	3111	200	200	200	120	120	120	200	0	120	10	10	200
78,0	117,0	75	25,0	3136	200	200	200	200	120	120	200	0	120	10	200	200
78,0	119,0	76	25,0	3161	200	200	200	200	200	120	200	0	120	200	200	200
78,0	121,0	77	25,0	3186	200	200	200	200	200	200	200	0	120	200	200	200
78,0	123,0	78	25,0	3211	200	200	200	200	200	200	200	0	120	200	200	200
78,0	125,0	79	25,8	3237	200	200	200	200	200	200	200	0	120	200	200	200
77,9	127,0	80	26,0	3263	200	200	200	200	200	200	200	0	120	200	200	200
77,8	129,0	81	26,2	3289	200	200	200	200	200	200	200	0	120	200	200	200
77,7	131,0	82	26,4	3315	200	200	120	200	200	200	200	0	120	200	200	200
77,6	133,0	83	26,6	3342	200	120	120	200	200	200	200	0	120	200	10	200
77,5	135,0	84	26,8	3368	200	120	120	120	200	200	200	0	120	200	10	200
77,4	137,0	85	27,0	3395	70	70	120	120	200	200	200	0	0	200	10	200
77,3	139,0	86	27,2	3423	70	70	120	120	200	120	200	0	0	10	10	30
77,2	141,0	87	27,4	3450	70	70	120	120	200	120	200	0	0	0	10	30
77,1	143,0	88	27,6	3478	70	70	120	120	120	120	120	0	0	0	10	30
77,0	145,0	89	33,9	3511	70	70	120	120	120	120	120	200	0	0	10	30
76,7	147,1	90	33,2	3545	70	70	120	120	120	120	120	0	0	0	10	30
76,4	149,1	91	33,7	3578	70	70	120	120	120	120	120	0	0	0	10	30
76,1	151,1	92	34,3	3613	70	70	120	120	120	120	120	0	0	0	10	30
75,8	153,1	93	33,5	3646	70	70	120	120	120	120	120	0	0	0	10	30
75,5	155,0	94	43,9	3690	70	70	120	120	120	120	120	0	0	0	10	30
75,0	157,1	95	44,7	3735	70	70	120	120	120	120	120	0	0	0	10	30
74,5	159,2	96	44,3	3779	70	70	120	120	120	120	120	0	0	0	10	30
74,0	161,2	97	43,8	3823	70	70	120	120	120	120	120	0	0	0	10	30
73,5	163,1	98	44,5	3868	70	70	120	120	120	120	120	0	0	0	10	30
73,0	165,0	99	44,3	3912	70	70	120	120	120	120	120	86	0	10	10	30
72,6	167,1	100	43,5	3955	70	70	120	120	120	120	120	0	0	10	10	30
72,2	169,1	101	44,2	4000	70	70	120	120	120	120	120	0	0	0	10	30
71,8	171,1	102	44,9	4044	70	70	120	120	120	120	120	0	0	0	10	30
71,4	173,1	103	43,9	4088	70	70	120	120	120	120	120	0	0	0	10	30
71,0	175,0	104	47,9	4136	70	70	120	120	120	120	120	0	120	0	10	30
70,6	177,1	105	46,9	4183	70	70	120	120	120	120	120	0	120	0	10	30
70,2	179,1	106	47,6	4231	70	70	120	120	120	120	120	0	120	0	10	30
69,8	-178,9	107	48,3	4279	70	70	120	120	120	120	0	0	0	0	10	30
69,4	-176,9	108	47,1	4326	70	70	120	120	120	120	0	0	0	0	10	30
69,0	-175,0	109	24,7	4351	70	70	120	120	120	120	0	0	0	0	0	30
68,8	-174,0	110	24,9	4376	70	30	120	120	120	120	0	0	0	0	0	30
68,6	-173,0	111	25,1	4401	70	30	120	120	120	120	0	0	0	0	0	30
68,4	-172,0	112	25,2	4426	70	30	120	120	120	120	0	0	0	0	0	30
68,2	-171,0	113	25,4	4451	70	30	120	120	120	120	0	0	0	0	0	30
68,0	-170,0	114	24,4	4476	70	30	70	120	120	120	0	0	0	0	0	30
67,6	-169,8	115	24,5	4500	30	30	30	120	70	120	0	0	0	0	0	30
67,2	-169,6	116	24,5	4525	30	30	30	120	70	0	0	0	0	0	0	30
66,8	-169,4	117	24,5	4549	30	30	30	120	70	0	0	0	0	0	0	30
66,4	-169,2	118	24,5	4574	30	30	70	120	70	0	0	0	0	0	0	30
66,0	-169,0	119	13,0	4587	30	30	70	120	70	0	0	0	0	0	0	30
65,8	-169,2	120	13,0	4600	30	30	30	70	70	0	0	0	0	0	0	10
65,6	-169,4	121	13,0	4613	30	30	30	70	70	0	0	0	0	0	0	10
65,4	-169,6	122	13,0	4626	30	30	30	70	70	0	0	0	0	0	0	10
65,2	-169,8	123	13,0	4639	30	30	30	70	70	0	0	0	0	0	0	10
65,0	-170,0	124	35,1	4674	30	30	30	70	70	0	0	0	0	0	0	0
64,6	-171,0	125	35,4	4709	30	30	30	70	70	0	0	0	0	0	0	0
64,2	-172,0	126	35,6	4745	30	30	30	70	70	0	0	0	0	0	0	0
63,8	-173,0	127	35,9	4781	30	30	30	70	70	0	0	0	0	0	0	0
63,4	-174,0	128	36,2	4817	30	30	30	70	70	0	0	0	0	0	0	0
63,0	-175,0	129	68,1	4885	30	30	30	70	70	0	0	0	0	0	0	0
62,4	-177,1	130	66,7	4952	30	30	0	70	0	0	0	0	0	0	0	0
61,8	-179,1	131	67,7	5020	30	30	0	70	0	0	0	0	0	0	0	0
61,2	178,9	132	68,6	5088	10	10	0	30	0	0	0	0	0	0	0	0
60,6	176,9	133	479,1	5567	0	0	0	0	0	0	0	0	0	0	0	0
55,7	165,0	134	674,8	6242	0	0	0	0	0	0	0	0	0	0	0	0
46,8	153,9	135	881,0	7123	0	0	0	0	0	0	0	0	0	0	0	0
35,7	141,2	136	43,6	7167	0	0	0	0	0	0	0	0	0	0	0	0
35,1	140,6	137	33,5	7200	0	0	0	0	0	0	0	0	0	0	0	0
34,8	140,0	138	10,8	7211	0	0	0	0	0	0	0	0	0	0	0	0
34,8	139,8	139	8,9	7220	0	0	0	0	0	0	0	0	0	0	0	0
35,0	139,7	140	8,1	7228	0	0	0	0	0	0	0	0	0	0	0	0
35,1	139,7	141	7,3	7235	0	0	0	0	0	0	0	0	0	0	0	0
35,2	139,8	142	2,9	7238	0	0	0	0	0	0	0	0	0	0	0	0
35,3	139,8	143	4,2	7242	0	0	0	0	0	0	0	0	0	0	0	0
35,3	139,7	144	7,7	7250	0	0	0	0	0	0	0	0	0	0	0	0
35,4	139,7	145	2,8	**7253**	0	0	0	0	0	0	0	0	0	0	0	0
35,5	139,7															

Table 11: Upper limits for ice thicknesses along the NSR

Latitude	Longitude	Waypoint	Distance [nm]	Cum. distance [nm]	January	February	March	April	Mai	June	July	August	September	October	November	December
51,9	4,5	1	0,3	0	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,5	2	0,5	1	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	3	0,5	1	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	4	0,4	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	5	0,4	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	6	0,3	2	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	7	0,2	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	8	0,2	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	9	0,4	3	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	10	0,5	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	11	0,2	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	12	0,3	4	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,4	13	0,6	5	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	14	0,4	5	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	15	0,4	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	16	0,3	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	17	0,4	6	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,3	18	2,5	9	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	19	1,0	10	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	20	1,2	11	0	0	0	0	0	0	0	0	0	0	0	0
51,9	4,2	21	3,2	14	0	0	0	0	0	0	0	0	0	0	0	0
52,0	4,1	22	3,3	18	0	0	0	0	0	0	0	0	0	0	0	0
52,0	4,0	23	6,4	24	0	0	0	0	0	0	0	0	0	0	0	0
52,0	3,9	24	214,7	239	0	0	0	0	0	0	0	0	0	0	0	0
55,5	5,4	25	139,7	378	0	0	0	0	0	0	0	0	0	0	0	0
57,8	5,0	26	89,2	468	0	0	0	0	0	0	0	0	0	0	0	0
59,3	4,3	27	165,3	633	0	0	0	0	0	0	0	0	0	0	0	0
62,0	4,0	28	145,1	778	0	0	0	0	0	0	0	0	0	0	0	0
64,4	5,0	29	238,2	1016	0	0	0	0	0	0	0	0	0	0	0	0
68,0	9,0	30	184,8	1201	0	0	0	0	0	0	0	0	0	0	0	0
70,4	14,5	31	166,4	1367	0	0	0	0	0	0	0	0	0	0	0	0
72,0	21,5	32	127,5	1495	0	0	0	0	0	0	0	0	0	0	0	0
72,4	28,3	33	125,7	1621	0	0	0	0	0	0	0	0	0	0	0	0
72,0	35,0	34	39,2	1660	0	0	0	0	0	0	0	0	0	0	0	0
71,8	37,0	35	41,4	1701	0	0	0	0	0	0	0	0	0	0	0	0
71,6	39,1	36	39,9	1741	0	0	0	0	0	0	0	0	0	0	0	0
71,4	41,1	37	38,5	1780	0	0	0	0	0	0	0	0	0	0	0	0
71,2	43,0	38	40,7	1820	0	0	0	0	0	0	0	0	0	0	0	0
71,0	45,0	39	41,1	1862	0	0	0	0	0	0	0	0	0	0	0	0
70,8	47,0	40	43,4	1905	0	0	0	0	0	0	0	0	0	0	0	0
70,6	49,1	41	44,0	1949	0	70	30	70	70	0	0	0	0	0	0	0
70,3	51,1	42	40,5	1989	0	70	70	70	70	0	0	0	0	0	0	0
70,1	53,0	43	42,8	2032	0	70	70	70	70	0	0	0	0	0	0	0
69,9	55,0	44	49,0	2081	0	70	70	70	70	0	0	0	0	0	0	0
70,4	56,9	45	48,3	2129	30	70	120	120	120	120	120	0	0	0	30	30
70,9	58,8	46	52,9	2182	70	70	120	120	120	120	120	0	0	0	30	30
71,5	60,8	47	49,6	2232	70	70	120	120	120	120	120	0	0	0	30	70
72,0	62,9	48	48,8	2281	70	120	120	120	120	120	120	0	0	0	30	70
72,5	65,0	49	41,6	2322	70	120	120	120	120	120	120	0	0	0	30	70
72,9	66,9	50	44,7	2367	70	120	120	120	120	200	200	0	0	0	30	70
73,4	68,8	51	41,5	2408	70	120	120	120	200	200	200	0	0	0	70	70
73,8	70,8	52	45,8	2454	70	120	120	200	200	200	200	0	0	30	70	70
74,3	72,9	53	41,4	2496	70	120	200	200	200	200	200	0	0	30	70	70
74,7	75,0	54	34,8	2531	70	120	200	200	200	200	200	0	0	30	70	70
75,0	76,9	55	35,7	2566	70	120	200	200	200	200	200	0	0	30	70	70
75,3	78,9	56	32,6	2599	120	120	200	200	200	200	200	0	0	0	70	70
75,5	80,9	57	34,8	2634	120	120	200	200	200	200	200	0	0	30	70	70
75,8	82,9	58	35,5	2669	120	120	200	200	200	200	200	0	0	30	70	70
76,1	85,0	59	29,7	2699	120	120	200	200	200	200	200	0	0	30	70	70
76,3	86,9	60	30,7	2729	120	120	200	200	200	200	200	200	0	30	70	120
76,5	88,9	61	30,3	2760	120	120	200	200	200	200	200	200	0	30	70	120
76,7	90,9	62	29,9	2790	120	120	300	200	200	200	200	300	0	30	300	120
76,9	92,9	63	30,8	2821	300	300	300	200	200	200	300	300	200	30	300	120
77,1	95,0	64	28,0	2848	300	300	300	200	200	200	300	300	0	30	300	120
77,3	96,9	65	28,8	2877	300	300	300	200	200	200	300	300	0	30	300	120
77,5	98,9	66	26,6	2904	300	300	300	300	300	200	300	300	200	30	300	120
77,6	100,9	67	28,3	2932	300	300	300	300	300	200	300	300	200	30	300	120
77,8	102,9	68	29,0	2961	300	300	300	300	300	300	300	300	200	30	300	120
78,0	105,0	69	25,0	2986	300	300	300	300	300	300	300	300	200	30	300	300
78,0	107,0	70	25,0	3011	300	300	300	300	300	300	300	300	0	30	300	300
78,0	109,0	71	25,0	3036	300	300	300	300	200	300	300	300	0	30	300	300
78,0	111,0	72	25,0	3061	300	300	300	300	200	300	300	300	0	300	300	300
78,0	113,0	73	25,0	3086	300	300	300	300	200	300	300	0	200	300	300	300

Table continues on the next page ...

Latitude	Longitude	Waypoint	Distance [nm]	Cum. distance [nm]	January	February	March	April	Mai	June	July	August	September	October	November	December
78,0	115,0	74	25,0	3111	300	300	300	300	200	300	300	0	200	300	300	300
78,0	117,0	75	25,0	3136	300	300	300	300	200	300	300	0	200	300	300	300
78,0	119,0	76	25,0	3161	300	300	300	300	300	300	300	300	200	300	300	300
78,0	121,0	77	25,0	3186	300	300	300	300	300	300	300	300	200	300	300	300
78,0	123,0	78	25,0	3211	300	300	300	300	300	300	300	300	200	300	300	300
78,0	125,0	79	25,8	3237	300	300	300	300	300	300	300	300	200	300	300	300
77,9	127,0	80	26,0	3263	300	300	300	300	300	300	300	300	200	300	300	300
77,8	129,0	81	26,2	3289	300	300	300	300	300	300	300	300	200	300	300	300
77,7	131,0	82	26,4	3315	300	300	300	300	300	300	300	300	200	300	300	300
77,6	133,0	83	26,6	3342	300	300	300	300	300	300	300	300	200	300	300	300
77,5	135,0	84	26,8	3368	300	300	300	300	300	300	300	300	200	300	300	300
77,4	137,0	85	27,0	3395	120	200	300	300	300	300	300	300	0	300	300	300
77,3	139,0	86	27,2	3423	120	200	300	300	300	300	300	300	0	300	300	70
77,2	141,0	87	27,4	3450	120	200	200	200	300	300	300	300	0	300	300	70
77,1	143,0	88	27,6	3478	120	200	200	200	300	200	300	300	0	30	300	70
77,0	145,0	89	33,9	3511	120	200	200	200	200	200	300	300	0	30	70	70
76,7	147,1	90	33,2	3545	120	200	200	200	200	200	300	200	0	30	70	70
76,4	149,1	91	33,7	3578	120	200	200	200	200	200	300	200	0	30	70	70
76,1	151,1	92	34,3	3613	120	200	200	200	200	200	200	200	0	30	70	70
75,8	153,1	93	33,5	3646	120	200	200	200	200	200	200	200	0	30	70	70
75,5	155,0	94	43,9	3690	120	200	200	200	200	200	200	200	0	30	70	70
75,0	157,1	95	44,7	3735	120	200	200	200	200	200	200	200	0	30	70	70
74,5	159,2	96	44,3	3779	120	200	200	200	200	200	200	200	0	30	70	70
74,0	161,2	97	43,8	3823	120	200	200	200	200	200	200	200	0	30	70	70
73,5	163,1	98	44,5	3868	120	200	200	200	200	200	200	200	0	30	70	70
73,0	165,0	99	44,3	3912	120	200	200	200	200	200	200	200	0	300	70	70
72,6	167,1	100	43,5	3955	120	200	200	200	200	200	200	200	0	300	70	70
72,2	169,1	101	44,2	4000	120	200	200	200	200	200	200	200	0	30	70	70
71,8	171,1	102	44,9	4044	120	200	200	200	200	200	200	200	0	30	70	70
71,4	173,1	103	43,9	4088	120	200	200	200	200	200	200	200	0	0	70	70
71,0	175,0	104	47,9	4136	120	200	200	200	200	200	200	200	200	0	70	70
70,6	177,1	105	46,9	4183	120	200	200	200	200	200	200	200	200	0	70	70
70,2	179,1	106	47,6	4231	120	200	200	200	200	200	200	0	200	0	70	70
69,8	-178,9	107	48,3	4279	120	200	200	200	200	200	0	0	0	0	70	70
69,4	-176,9	108	47,1	4326	120	200	200	200	200	200	0	0	0	0	70	70
69,0	-175,0	109	24,7	4351	120	200	200	200	200	200	0	0	0	0	30	70
68,8	-174,0	110	24,9	4376	120	120	200	200	200	200	0	0	0	0	30	70
68,6	-173,0	111	25,1	4401	120	120	200	200	200	200	0	0	0	0	30	70
68,4	-172,0	112	25,2	4426	120	120	200	200	200	200	0	0	0	0	30	70
68,2	-171,0	113	25,4	4451	120	120	200	200	200	200	0	0	0	0	30	70
68,0	-170,0	114	24,4	4476	120	120	200	200	200	200	0	0	0	0	30	70
67,6	-169,8	115	24,5	4500	70	120	120	200	200	200	0	0	0	0	30	70
67,2	-169,6	116	24,5	4525	70	120	120	200	200	200	0	0	0	0	30	70
66,8	-169,4	117	24,5	4549	70	120	120	200	200	200	0	0	0	0	30	70
66,4	-169,2	118	24,5	4574	70	70	120	200	200	200	0	0	0	0	30	70
66,0	-169,0	119	13,0	4587	70	70	120	200	120	200	0	0	0	0	30	70
65,8	-169,2	120	13,0	4600	70	70	120	120	120	200	0	0	0	0	30	30
65,6	-169,4	121	13,0	4613	70	70	120	120	120	200	0	0	0	0	30	30
65,4	-169,6	122	13,0	4626	70	70	120	120	120	200	0	0	0	0	30	30
65,2	-169,8	123	13,0	4639	70	70	120	120	120	200	0	0	0	0	30	30
65,0	-170,0	124	35,1	4674	70	70	120	120	120	120	0	0	0	0	30	0
64,6	-171,0	125	35,4	4709	70	70	120	120	120	120	0	0	0	0	30	0
64,2	-172,0	126	35,6	4745	70	70	70	120	120	120	0	0	0	0	30	0
63,8	-173,0	127	35,9	4781	70	70	70	120	120	120	0	0	0	0	0	0
63,4	-174,0	128	36,2	4817	70	70	70	120	120	120	0	0	0	0	0	0
63,0	-175,0	129	68,1	4885	70	70	120	120	120	120	0	0	0	0	0	0
62,4	-177,1	130	66,7	4952	70	70	120	120	120	0	0	0	0	0	0	0
61,8	-179,1	131	67,7	5020	70	70	70	120	120	0	0	0	0	0	0	0
61,2	178,9	132	68,6	5088	30	70	70	120	0	0	0	0	0	0	0	0
60,6	176,9	133	479,1	5567	0	30	70	70	0	0	0	0	0	0	0	0
55,7	165,0	134	674,8	6242	0	0	0	0	0	0	0	0	0	0	0	0
46,8	153,9	135	881,0	7123	0	0	0	0	0	0	0	0	0	0	0	0
35,7	141,2	136	43,6	7167	0	0	0	0	0	0	0	0	0	0	0	0
35,1	140,6	137	33,5	7200	0	0	0	0	0	0	0	0	0	0	0	0
34,8	140,0	138	10,8	7211	0	0	0	0	0	0	0	0	0	0	0	0
34,8	139,8	139	8,9	7220	0	0	0	0	0	0	0	0	0	0	0	0
35,0	139,7	140	8,1	7228	0	0	0	0	0	0	0	0	0	0	0	0
35,1	139,7	141	7,3	7235	0	0	0	0	0	0	0	0	0	0	0	0
35,2	139,8	142	2,9	7238	0	0	0	0	0	0	0	0	0	0	0	0
35,3	139,8	143	4,2	7242	0	0	0	0	0	0	0	0	0	0	0	0
35,3	139,7	144	7,7	7250	0	0	0	0	0	0	0	0	0	0	0	0
35,4	139,7	145	2,8	**7253**	0	0	0	0	0	0	0	0	0	0	0	0
35,5	139,7															

In the following figures the developed Matlab Scripts are presented. These form beside the Simevents simulation the core of this thesis.

```
/Users/schartmueller/Docume.../transit_time_generation.m    1 of 1

% Bernhard Schartmueller | bernhard.schartmueller@gmail.com | September
% 2014
% Generation of Transit times for input for the Simevents Simulation
%-------------------------------------------------------
% Input data for the functions
%-------------------------------------------------------
ice_scenario_concentration=1;
    % Selection of the ice scenario for sensitivity study e.g. for
    % ice_scenario_concentration=0.6 it means that of the ice data 60%
    % of the original ice thickness
    % is used in the calculations
ice_scenario_thickness=1;
    % Selection of the ice scenario for sensitivity study e.g. for
    % ice_scenario_thickness=0.6 it means that 60% of the original ice
    % thickness is used in the calculations
v_desired_skalar=24; % desired Vessel speed
cargo_capacity_TEU=4402;
    % Cargo capacity in TEU
    % cargo_capacity_TEU=4402; for CV4400 ICE
    % cargo_capacity_TEU=8160; for CV8160
    % cargo_capacity_TEU=2300; for CV2300
%-------------------------------------------------------
% Transit time generation
%-------------------------------------------------------
% Transit times for the Northern Sea Route
[NSR_transit_information]=NSR_transit_time_function(v_desired_skalar,↙
ice_scenario_thickness,ice_scenario_concentration,NSR_CT_lower_limit,↙
NSR_CT_upper_limit,NSR_thickness_lower_limit,NSR_thickness_upper_limit,NSR_waypoints);
% Transit times for the Suez Canal Route
[SUEZ_transit_information]=SUEZ_transit_time_function(v_desired_skalar,↙
SUEZ_waypoints);
%-------------------------------------------------------
% randomize seeds of Simevents Model
%-------------------------------------------------------
% ldFormat = get(0, 'Format');
% format long;
% modelname = 'dsm';
% se_randomizeseeds(modelname, 'GlobalSeed', 2337)
```

Fig. 38: Matlab Script for executing transit time generation scripts for NSR and SCR

```matlab
function [NSR_transit_information]=NSR_transit_time_function(v_desired_skalar,↙
ice_scenario_thickness,ice_scenario_concentration,NSR_CT_lower_limit,↙
NSR_CT_upper_limit,NSR_thickness_lower_limit,NSR_thickness_upper_limit,NSR_waypoints)
% Bernhard Schartmueller | bernhard.schartmueller@gmail.com | September
% 2014
% This function calculates the transit time and fuel consumption for
% a certain speed of the vessel
%rng('default')
NSR_transit_information=zeros(365,3);
[courses,distances]=legs(NSR_waypoints); % Leg distances
di=length(distances); % Length of the "distances" vector
for year=0:19
for day=1:365
    if day>=0 && day<=31 % Selecting month for ice data
        month=1;
    elseif day>31 && day<=59
        month=2;
    elseif day>59 && day<=90
        month=3;
    elseif day>90 && day<=120
        month=4;
    elseif day>120 && day<=151
        month=5;
    elseif day>151 && day<=181
        month=6;
    elseif day>181 && day<=212
        month=7;
    elseif day>212 && day<=243
        month=8;
    elseif day>243 && day<=273
        month=9;
    elseif day>273 && day<=304
        month=10;
    elseif day>304 && day<=334
        month=11;
    else
        month=12;
    end
NSR_CT_rand=zeros(di,1);
NSR_CT_rand_distance_noicepart=zeros(di,1);
NSR_CT_rand_distance_icepart=zeros(di,1);
for j=1:di
    a=NSR_CT_lower_limit(j,month).*ice_scenario_concentration./100;
    b=NSR_CT_upper_limit(j,month).*ice_scenario_concentration./100;
    NSR_CT_rand(j,1)=(b-a).*rand(1,1)+a;
    NSR_CT_rand_distance_icepart(j,1)=NSR_CT_rand(j,1)*distances(j,1);
    NSR_CT_rand_distance_noicepart(j,1)=(1-NSR_CT_rand(j,1))*distances(j,1);
end
NSR_thickness_rand=zeros(20,1);
for k=1:di
    a=NSR_thickness_lower_limit(k,month).*ice_scenario_thickness./100;
    b=NSR_thickness_upper_limit(k,month).*ice_scenario_thickness./100;
    NSR_thickness_rand(k,1)=(b-a).*rand(1,1)+a;
end
Hm=NSR_thickness_rand(:,1); % brash ice thickness in channel
% --------------------------------------------
% input for ship parameters
% --------------------------------------------
% ship paramteres for vessel CV4400 ICE
% --------------------------------------------
  L=294;    % length OA of vessel (m)
  Lpp=281; % length perpendicular (m)
```

```
  Lwl=1.01*Lpp; % approximate Formula for the length waterline (m)
  Lpar=0.5*L; % length of parallell midbody (m)
  Lbow=0.25*L; % Assumption from analysis from pictures of the vessel
  T=10.78;    % draught of vessel (m)
  B=32.2;      % beam of vessel
  eta_t=0.878; % total efficiency
  sfc=180; % specific fuel consumption [g/kWh]
  Dp=6.556; % diameter propeller [m]
% ----------------------------------------------
% ship paramteres for vessel CV2300
% ----------------------------------------------
% L=185;   % length OA of vessel (m)
% Lpp=177; % length perpendicular (m)
% Lwl=1.01*Lpp; % approximate Formula for the length waterline (m)
% Lpar=0.5*L; % length of parallell midbody (m)
% Lbow=0.25*L; % Assumption from analysis from pictures of the vessel
% T=8.5;    % draught of vessel (m)
% B=30.4;      % beam of vessel
% eta_t=0.853; % total efficiency
% sfc=180; % specific fuel consumption [g/kWh]
% Dp=5.136; % diameter propeller
% ----------------------------------------------
% Ice Resistance (Brash Ice channel resistance)
% input for ice resistance
    % Assumptions:
    % uB=0.8 uB=1-p normal values:(uB=0.8 ... 0.9)
    % pDelta=150 difference between the densities of water and ice
    % g=9.81 m/(s^2)
Kp=6.5; % coefficient of passive stress
phi=90; % stem angle, 90° if bulb
alpha=23; % angle between the waterline and the vertical at B/4
psi=atand(tand(phi)/sind(alpha)); % flare angle
uh=0.02; % coefficient of friction between hull and ice
K0=0.68; % coefficient of lateral stress at rest
Kp_propeller_type=2.26; % Fixed Pitch propeller
K=0.78; %
Awf=Lbow*B/2; % area of waterline at bow (SEE FSICR) (m2)
v_icepart=zeros(di,1);
v_noicepart=zeros(di,1);
v_from_h_v=zeros(di,1);
Rch=zeros(di,1);
Row_icepart=zeros(di,1);
Row_noicepart=zeros(di,1);
PEice_icepart=zeros(di,1);
PEow_icepart=zeros(di,1);
PEow_noicepart=zeros(di,1);
PEtotal_icepart=zeros(di,1);
PEService_icepart=zeros(di,1);
PEService_noicepart=zeros(di,1);
Pp_icepart=zeros(di,1);
Pp_noicepart=zeros(di,1);
fuel_tonperday_legs_icepart=zeros(di,1);
fuel_tonperday_legs_noicepart=zeros(di,1);
fuelconsumption_legs_icepart=zeros(di,1);
fuelconsumption_legs_noicepart=zeros(di,1);
fuelconsumption_legs_total=zeros(di,1);
travel_time_icepart=zeros(di,1);
travel_time_noicepart=zeros(di,1);
travel_time=zeros(di,1);
for i=1:di
v_noicepart(i,1)=v_desired_skalar+0.5.*randn(1,1);
    % create "random" speed according to Normal distribution with
```

```
    % mean=v_desired_skalar and standard deviation=0.5
if Hm(i,1)==0        % Channel resistance is 0 if there is no ice
    Rch(i,1)=0;
    v_icepart(i,1)=0;
else         % in case ice occurs
    if NSR_CT_rand(i,1)>0.3
        % 30 % rule, under 30 % the ship can sail (nearly) at
        % open water speed because they can go around the ice floes
        v_noicepart(i,1)=10+0.5.*randn(1,1);
    else
        v_noicepart(i,1)=v_desired_skalar+0.5.*randn(1,1);
        % create "random" speed according to Normal distribution with
        % mean=v_desired_skalar and standard deviation=0.5
    end
    % Check speed in ice for given ice thickness Hm
    v_from_h_v(i,1)=hv_speedinice(Hm(i,1));
    % calculates the max. possible speed for a given ice thickness
    if v_from_h_v(i,1)<3
        % sets the ship speed to 3 knots in case the speed
        % from the h-v curve is below this value
        v_from_h_v(i,1)=3;
    end
    if v_from_h_v(i,1)>=10 && v_desired_skalar>=10
        % to avoid damage to the ship due to single ice flows in
        % the brash ice channel the ship goes
        % max. 10 knots also if it could go faster
        v_icepart(i,1)=10+0.5.*randn(1,1);
    elseif v_desired_skalar<10 && v_desired_skalar<v_from_h_v(i,1)
        % when the desired speed is smaller then the possible speed in ice
        % it still goes with the desired speed, interesting
        % for slow steaming
        v_icepart(i,1)=v_desired_skalar+0.5.*randn(1,1);
    else
        v_icepart(i,1)=v_from_h_v(i,1);
        % if the calculated speed from the h-v curve is below the
        % max. speed of 10 knots, this speed is taken for further calculation
    end
        if B>10 && Hm(i,1)>0.4
            Hf=0.26+(B*Hm(i,1)).^0.5;
Rch(i,1)=0.5.*0.8.*150.*9.81.*Hf.^(2).*Kp.*(0.5+(Hm(i,1)./(2.*Hf))).^(2).*(B+(2.*Hf).↙
*...   % in [N] because delta_rho is in [kg/(m^3)]
            (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(i,↙
1).*Awf.*(0.514444*v_icepart(i,1)./sqrt( 9.81.*L)).^2;
        else
            Hf=Hm(i,1)+(B./2).*tand(2)+(tand(2)+tand(22.6)).*sqrt((B.*(Hm(i,1)+(B./4).↙
*tand(2))./(tand(2)+tand(22.6))));
            Rch(i,1)=0.5.*0.8.*150.*9.81.*Hf^(2).*Kp.*(0.5+(Hm(i,1)./(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(i,↙
1).*Awf.*(0.514444*v_icepart(i,1)./sqrt(9.81.*L)).^2;
        end
end
% -------------------------------------------
% Open Water Resistance
% -------------------------------------------
% Row for vessel CV4400 ICE
 p1=0.2191;
 p2=-8.697;
 p3=118.2;
```

```
 p4=2193;
 p5=2393;
 p6=-436;
 Row_icepart(i,1)=p1*v_icepart(i,1)^5+p2*v_icepart(i,1)^4+p3*v_icepart(i,1)↙
^3+p4*v_icepart(i,1)^2+p5*v_icepart(i,1)+p6; % in [N]
 Row_noicepart(i,1)=p1*v_noicepart(i,1)^5+p2*v_noicepart(i,1)^4+p3*v_noicepart(i,1)↙
^3+p4*v_noicepart(i,1)^2+p5*v_noicepart(i,1)+p6; % in [N]
% -------------------------------------------
% Row for vessel CV2300
% a=4.295e-10;
% b=1.457;
% c=3.274e+04;
% d=0.1722;
% Row_icepart(i,1)=a*exp(b*v_icepart(i,1))+c*exp(d*v_icepart(i,1));
% in [N]
% Row_noicepart(i,1)=a*exp(b*v_noicepart(i,1))+c*exp(d*v_noicepart(i,1));
% in [N]
% -------------------------------------------
PEice_icepart(i,1)=Kp_propeller_type.*(Rch(i,1)./1000./Dp).^(3/2);
%FSICR
PEow_icepart(i,1)=Row_icepart(i,1)./1000.*v_icepart(i,1).*0.51444;
% PE Effective (towing) Power [kW]
% ... Division /1000 to bring the Resistance from [N] to [kN]
PEtotal_icepart(i,1)=PEice_icepart(i,1)+PEow_icepart(i,1);
PEow_noicepart(i,1)=Row_noicepart(i,1)./1000.*v_noicepart(i,1).*0.51444;
% PE Effective (towing) Power [kW] ...
% Division /1000 to bring the Resistance from [N] to [kN]
PEService_icepart(i,1)=PEtotal_icepart(i,1)*1.25;
% PEService [kW] 1.25
PEService_noicepart(i,1)=PEow_noicepart(i,1).*1.25;
% PEService [kW]
Pp_icepart(i,1)=PEService_icepart(i,1)./eta_t; % Pp Propulsion Power [kW]
Pp_noicepart(i,1)=PEService_noicepart(i,1)./eta_t; % Pp Propulsion Power [kW]
fuel_tonperday_legs_icepart(i,1)=(((sfc./(3600./Pp_icepart(i,1))).*3600)./1000).*24.↙
/1000;
fuel_tonperday_legs_noicepart(i,1)=(((sfc/(3600/Pp_noicepart(i,1)))*3600)/1000)↙
*24/1000;
% travel time calculation
travel_time_noicepart(i,1)=NSR_CT_rand_distance_noicepart(i,1)./v_noicepart(i,1)./24;
if v_icepart(i,1)==0 % avoids error due to division by zero if there is no ice
    travel_time_icepart(i,1)=0;
else
    travel_time_icepart(i,1)=NSR_CT_rand_distance_icepart(i,1)./v_icepart(i,1)./24;
end
travel_time(i,1)=travel_time_noicepart(i,1)+travel_time_icepart(i,1); % total travel↙
time
fuelconsumption_legs_icepart(i,1)=travel_time_icepart(i,1).↙
*fuel_tonperday_legs_icepart(i,1);
fuelconsumption_legs_noicepart(i,1)=travel_time_noicepart(i,1).↙
*fuel_tonperday_legs_noicepart(i,1);
fuelconsumption_legs_total(i,1)=fuelconsumption_legs_icepart(i,1)↙
+fuelconsumption_legs_noicepart(i,1);
end
NSR_transit_information(day,1)=month;
NSR_transit_information(day,2)=sum(travel_time);
NSR_transit_information(day,3)=sum(fuelconsumption_legs_total);
end
year_string=sprintf('NSR_transit_information_%d',year);
assignin('base', year_string, NSR_transit_information);
end
end
```

Fig. 39: Matlab Script for transit time generation for the NSR

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```
function [v] = hv_speedinice(Hm)
% Bernhard Schartmueller | bernhard.schartmueller@gmail.com | September
% 2014
% calculates the max. possible speed for a given ice thickness
% --------------------------------------------
% CV4400 ICE
% --------------------------------------------
p1=-0.29;
p2=1.801;
p3=-4.902;
p4=7.917;
p5=-14.47;
p6=24.59;
v=p1*Hm.^5+p2*Hm.^4+p3*Hm.^3+p4*Hm.^2+p5*Hm+p6;
% --------------------------------------------
% --------------------------------------------
% CV2300
% --------------------------------------------
%  p1=-4.622;
%  p2=16.78;
%  p3=-22.21;
%  p4=9.867;
%  p5=-7.068;
%  p6=18.38;
% v=p1*Hm.^5+p2*Hm.^4+p3*Hm.^3+p4*Hm.^2+p5*Hm+p6;
% --------------------------------------------
end
```

Fig. 40: Matlab script for calculation of the vessel speed in ice

```
function [SUEZ_transit_information]=SUEZ_transit_time_function(v_desired_skalar,↙
SUEZ_waypoints)
% This function calculates the transit time and the fuel consumption for a
% certain vessel for the Suez Route
% Bernhard Schartmueller | bernhard.schartmueller@gmail.com | September
% 2014
%rng('default')
SUEZ_transit_information=zeros(365,3);
v_suez_canal=8; % Average speed in Suez Canal is assumed to be 8 knots
[courses,distances]=legs(SUEZ_waypoints); % Leg distances
di=length(distances); % Length of the "distances" vector
% --------------------------------------------
% input for ship parameters
% --------------------------------------------
% ship paramteres for vessel CV4400 ICE
% --------------------------------------------
 eta_t=0.878; % total efficiency
 sfc=180; % specific fuel consumption [g/kWh]
% --------------------------------------------
% ship paramteres for vessel CV2300
% --------------------------------------------
% eta_t=0.853; % total efficiency
% sfc=180; % specific fuel consumption [g/kWh]
% --------------------------------------------
% ship paramteres for vessel CV8160
% --------------------------------------------
% eta_t=0.700; % total efficiency
% sfc=180; % specific fuel consumption [g/kWh]
% --------------------------------------------
for year=0:19
for day=1:365
    v_noicepart=zeros(di,1);
    Row_noicepart=zeros(di,1);
    PEow_noicepart=zeros(di,1);
    PEService_noicepart=zeros(di,1);
    Pp_noicepart=zeros(di,1);
    fuel_tonperday_legs_noicepart=zeros(di,1);
    fuelconsumption_legs_noicepart=zeros(di,1);
    fuelconsumption_legs_total=zeros(di,1);
    travel_time_noicepart=zeros(di,1);
    travel_time=zeros(di,1);
 for i=1:di
    if i>=42 && i<=59
        v_noicepart(i,1)=v_suez_canal+0.5.*randn(1,1);
    else
    v_noicepart(i,1)=v_desired_skalar+0.5.*randn(1,1); % create "random" speed↙
according to Normal distribution with
                                                 % mean=v_desired_skalar and standard↙
deviation=0.5
    end
% --------------------------------------------
% Open Water Resistance
% --------------------------------------------
% Row for vessel CV4400 ICE
 p1=0.2191;
 p2=-8.697;
 p3=118.2;
 p4=2193;
 p5=2393;
 p6=-436;
 Row_noicepart(i,1)=p1*v_noicepart(i,1)^5+p2*v_noicepart(i,1)^4+p3*v_noicepart(i,1)↙
^3+p4*v_noicepart(i,1)^2+p5*v_noicepart(i,1)+p6; % in [N]
```

```
% -------------------------------------------
% Row for vessel CV2300
% a=4.295e-10;
% b=1.457;
% c=3.274e+04;
% d=0.1722;
% Row_noicepart(i,1)=a*exp(b*v_noicepart(i,1))+c*exp(d*v_noicepart(i,1)); % in [N]
% -------------------------------------------
% Row for vessel CV8160
% p1=-0.01999;
% p2=1.575;
% p3=-31.97;
% p4=4238;
% p5=1569;
% p6=-227.8;
% Row_noicepart(i,1)=p1*v_noicepart(i,1)^5+p2*v_noicepart(i,1)^4+p3*v_noicepart(i,1)↙
^3+p4*v_noicepart(i,1)^2+p5*v_noicepart(i,1)+p6; % in [N]
% -------------------------------------------
PEow_noicepart(i,1)=Row_noicepart(i,1)./1000.*v_noicepart(i,1).*0.51444; % PE↙
Effective (towing) Power [kW] ... Division /1000 to bring the Resistance from [N] to↙
[kN]
PEService_noicepart(i,1)=PEow_noicepart(i,1).*1.25; % PEService [kW]
Pp_noicepart(i,1)=PEService_noicepart(i,1)./eta_t; % Pp Propulsion Power [kW]
fuel_tonperday_legs_noicepart(i,1)=(((sfc/(3600/Pp_noicepart(i,1)))*3600)/1000)↙
*24/1000;
% travel time calculation
travel_time_noicepart(i,1)=distances(i,1)./v_noicepart(i,1)./24;
travel_time(i,1)=travel_time_noicepart(i,1); % total travel time
fuelconsumption_legs_noicepart(i,1)=travel_time_noicepart(i,1).↙
*fuel_tonperday_legs_noicepart(i,1);
fuelconsumption_legs_total(i,1)=fuelconsumption_legs_noicepart(i,1);
 end
SUEZ_transit_information(day,1)=0; %month
SUEZ_transit_information(day,2)=sum(travel_time);
SUEZ_transit_information(day,3)=sum(fuelconsumption_legs_total);
end
year_string=sprintf('SUEZ_transit_information_%d',year);
assignin('base', year_string, SUEZ_transit_information);
end
end
```

Fig. 41: Matlab Script for transit time generation for the SCR

Resistance calculation following the procedure described in *Prediction of Resistance and Propulsion Power of Ships*(Kristensen and Lützen 2012) that is based on Guldhammer/Harvald

	Unit	Vessel data CV 2300	The vessel data is obtained from Grontmij (Grontmij 2012) or based on values from this source
LOA	[m]	185	
Lpp	[m]	177	alternative calculation using formula: LPP=0.97*LWL
CB - Block Coefficient		0,65	(MAN 2011)
T - Draught Amidship	[m]	8,5	
Cargo capacity	[TEU]	2318	(source: http://www.marineshipdesign.com/media/1484/SEA_DRAGON_2300_TEU_Container_Feeder.pdf)
Lwl	[m]	178,77	LWL=1,01*LPP
Beam (max) - breath moulded	[m]	30,40	
Design draught	[m]	8,5	
Displacement	[kg]	30472143,00	30472,143 [ton]
Displaced volume	[m^3]	29728,92	
Slenderness ratio - (Schlankheitsgrad)		5,77	formula: L/Displacement^(1/3) --> Graph for 6
B/T	-	3,58	
Cm-Midship coefficient	-	0,98	Kerlen (1970)
Cp - Prismatic coefficient	-	0,66	DTU p.8
Wetted surface	[m^2]	6352,73	DTU p.4
1 knot	[m/s]	0,51	
g	[m/(s^2)]	9,81	
Kinematic viscosity	[(m^2)/s]	0,00000114	
Density saltwater	[kg/(m^3)]	1025,00	
	[t/(m^3)]	1,03	

Calculation

Speed [kn]	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Speed [m/s]		0,514	1,029	1,543	2,058	2,572	3,087	3,601	4,116	4,630	5,144	5,659	6,173
Froudes number [-]		0,012	0,025	0,037	0,049	0,061	0,074	0,086	0,098	0,111	0,123	0,135	0,147
Reynolds number [-]		80708403,15	161416806,3	242125209	322833613	403542016	484250419	564958822	645667225	726375628	807084031	887792435	968500838
Resistance calculations													
Cf - Friction coefficient		2,15E-03	1,95E-03	1,84E-03	1,77E-03	1,72E-03	1,68E-03	1,65E-03	1,62E-03	1,59E-03	1,57E-03	1,55E-03	1,54E-03
CA - Correction scale + rough		2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04
CAA Air Resistance Coefficient		9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05
CR,Diagramm		5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04
DeltaCR,B/T		1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04
Correction Bulb		-4,35E-04	-4,19E-04	-4,04E-04	-3,89E-04	-3,73E-04	-3,58E-04	-3,43E-04	-3,27E-04	-3,12E-04	-2,96E-04	-2,81E-04	-2,66E-04
CR		2,38E-04	2,53E-04	2,68E-04	2,84E-04	2,99E-04	3,14E-04	3,30E-04	3,45E-04	3,60E-04	3,76E-04	3,91E-04	4,07E-04
CT Total resistance coefficient		2,72E-03	2,53E-03	2,44E-03	2,38E-03	2,35E-03	2,32E-03	2,30E-03	2,29E-03	2,28E-03	2,28E-03	2,27E-03	2,27E-03
RT Total resistance [N]	**0**	**2340**	**8711**	**18898**	**32843**	**50538**	**71995**	**97243**	**126320**	**159269**	**196138**	**236981**	**281853**
RT Total resistance [kN]		2	9	19	33	51	72	97	126	159	196	237	282
PE Effective (towing) Power [Watt]		1203,690646	8962,653376	29165,5526	67583,8575	129993,722	222224,245	350183,78	519876,485	737413,645	1009021,89	1341049,43	1739970,92
PE Effective (towing) Power[kW]		**1**	**9**	**29**	**68**	**130**	**222**	**350**	**520**	**737**	**1009**	**1341**	**1740**
PEService [kW]		2	11	36	84	162	278	438	650	922	1261	1676	2175

Speed [kn]	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Speed [m/s]	6,688	7,202	7,717	8,231	8,746	9,260	9,774	10,289	10,803	11,318	11,832	12,347
Froudes number [-]	0,160	0,172	0,184	0,197	0,209	0,221	0,233	0,246	0,258	0,270	0,283	0,295
Reynolds number [-]	1049209241	1129917644	1210626047	1291334450	1372042854	1452751257	1533459660	1614168063	1694876466	1775584869	1856293272	1937001676
Resistance calculations												
Cf - Friction coefficient	1,52E-03	1,51E-03	1,49E-03	1,48E-03	1,47E-03	1,46E-03	1,45E-03	1,44E-03	1,44E-03	1,43E-03	1,42E-03	1,41E-03
CA - Correction scale + rough	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04	2,31E-04
CAA Air Resistance Coefficient	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05	9,70E-05
CR,Diagramm	5,00E-04	5,00E-04	6,00E-04	7,00E-04	8,00E-04	9,50E-04	1,00E-03	1,40E-03	1,80E-03	2,10E-03	2,70E-03	4,20E-03
DeltaCR,B/T	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04	1,72E-04
Correction Bulb	-2,50E-04	-2,35E-04	-2,64E-04	-2,86E-04	-3,02E-04	-3,30E-04	-3,16E-04	-4,00E-04	-4,59E-04	-4,71E-04	-5,23E-04	-6,84E-04
CR	4,22E-04	4,37E-04	5,09E-04	5,86E-04	6,70E-04	7,92E-04	8,56E-04	1,17E-03	1,51E-03	1,80E-03	2,35E-03	3,69E-03
CT Total resistance coefficient	2,27E-03	2,27E-03	2,33E-03	2,40E-03	2,47E-03	2,58E-03	2,64E-03	2,94E-03	3,28E-03	3,56E-03	4,10E-03	5,43E-03
RT Total resistance [N]	**330811**	**383916**	**452099**	**528903**	**615207**	**721065**	**820147**	**1014711**	**1245072**	**1483239**	**1867619**	**2694305**
RT Total resistance [kN]	331	384	452	529	615	721	820	1015	1245	1483	1868	2694
PE Effective (towing) Power [Watt]	2212391,355	2765049,269	3488697,63	4353461,25	5380324,63	6677056,8	8016477,33	10440246,7	13450928,9	16786966,5	22098075,3	33265677,6
PE Effective (towing) Power[kW]	**2212**	**2765**	**3489**	**4353**	**5380**	**6677**	**8016**	**10440**	**13451**	**16787**	**22098**	**33266**
PEService [kW]	2765	3456	4361	5442	6725	8346	10021	13050	16814	20984	27623	41582

Propulsive Efficiencies

FA	0	
a	0,16600509	
b	0,45750255	
c	68,48663265	
w1	0,29818526	
w2	0	0 for normal N-shaped hull
w3	0,06603884	w3 <=0,1
Dprop Propeller Diameter	5,136	
wake fraction w	0,364	
d	0,186	
e	0,122	
f	-258,589	
t1	0,172	
t2	0,000	0 for normal N-shaped hull
t3	-0,023	
thrust deduction fraction t	0,149	

Hull efficiency:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
hull efficiency ηH		1,339	1,339	1,339	1,339	1,339	1,339	1,339	1,339	1,339	1,339	1,339	1,339
VA		0,327	0,654	0,981	1,308	1,635	1,962	2,289	2,617	2,944	3,271	3,598	3,925
Propeller efficiency ηO													
Cth thrust loading coefficient		2,421	2,253	2,173	2,124	2,092	2,069	2,053	2,042	2,035	2,029	2,027	2,025
ηO		0,545	0,555	0,561	0,564	0,566	0,568	0,569	0,569	0,570	0,570	0,571	0,571
		0,650	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**
ηR		1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
ηS		0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980
ηT		0,853	0,853	0,853	0,853	0,853	0,853	0,853	0,853	0,853	0,853	0,853	0,853
--> adopted ηT due to the uncertainties of													
the calculation --> formula only optimized for certain ship sizes													
Pp Propulsion Power		1,765	13,139	42,756	99,076	190,568	325,776	513,362	762,127	1081,032	1479,204	1965,949	2550,759

Calculation is continued on next page ...

... Calculation continued from previous page.

		13	14	15	16	17	18	19	20	21	22	23	24
hull efficiency η_H		1,339	1,339	1,339	1,339	1,339	1,339	1,339	1,339	1,339	1,339	1,339	1,339
VA		4,252	4,579	4,906	5,233	5,560	5,887	6,214	6,541	6,868	7,196	7,523	7,850
Propeller efficiency η_O													
Cth thrust loading coefficient		2,025	2,027	2,079	2,138	2,203	2,303	2,351	2,625	2,921	3,171	3,653	4,840
η_O (not lower than 0,65)		0,571	0,571	0,567	0,563	0,559	0,552	0,549	0,533	0,516	0,503	0,481	0,434
		0,650	**0,650**	**0,650**									
η_R		1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
η_S		0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980
η_T		0,853	0,853	0,853	0,853	0,853	0,853	0,853	0,853	0,853	0,853	0,853	0,853
--> adopted η_T due to the uncertainties of the calculation for big ships like the Sofie Maersk													
Pp Propulsion Power		3243,317	4053,501	5114,354	6382,078	7887,437	9788,418	11751,979	15305,171	19718,765	24609,322	32395,290	48766,749

Electrical Power Consumption:			
Number of refeers:		0	Comment: This function is optional and not used for the case study
Power per refeer incl. Vent	[kW]	8,15	
Power consumption for refeers:	[kW]	0	
Electrical	[kW]	1275	Main diesel generators, 900 rpm 4 x 1,500 kW
Total:	[kW]	1275	
additional fuel consumption per day	[kg/day]	5508	
	[ton/day]	5,508	
specific fuel consumption	[g/kWh]	180	Calculation with fixed specific fuel consumption
Fuel oil density	[kg/m^3]	900	

		0	1	2	3	4	5	6	7	8	9	10	11	12
Time needed to produce 1 kWh	[s]		2040,14	273,99	84,20	36,34	18,89	11,05	7,01	4,72	3,33	2,43	1,83	1,41
Fuel consumption per second	[g/s]		0,09	0,66	2,14	4,95	9,53	16,29	25,67	38,11	54,05	73,96	98,30	127,54
Fuel consumption per hour	[g/hr]		317,63	2365,03	7696,09	17833,76	34302,23	58639,65	92405,10	137182,94	194585,78	266256,68	353870,79	459136,61
Fuel consumption per hour	[kg/hr]		0,32	2,37	7,70	17,83	34,30	58,64	92,41	137,18	194,59	266,26	353,87	459,14
Fuel consumption per hour	[m^3/hr]		0,000352917	0,00262781	0,00855121	0,01981529	0,03811359	0,06515517	0,10267234	0,15242549	0,21620642	0,29584076	0,39318977	0,51015179
Fuel consumption per day	**[ton/day]**	**0**	**0,007623**	**0,0567607**	**0,184706**	**0,42801**	**0,823253**	**1,407352**	**2,217722**	**3,292391**	**4,670059**	**6,39016**	**8,492899**	**11,01928**

		13	14	15	16	17	18	19	20	21	22	23	24
Time needed to produce 1 kWh	[s]	1,11	0,89	0,70	0,56	0,46	0,37	0,31	0,24	0,18	0,15	0,11	0,07
Fuel consumption per second	[g/s]	162,17	202,68	255,72	319,10	394,37	489,42	587,60	765,26	985,94	1230,47	1619,76	2438,34
Fuel consumption per hour	[g/hr]	583797,03	729630,21	920583,66	1148774,04	1419738,67	1761915,20	2115356,16	2754930,78	3549377,63	4429677,98	5831152,26	8778014,74
Fuel consumption per hour	[kg/hr]	583,80	729,63	920,58	1148,77	1419,74	1761,92	2115,36	2754,93	3549,38	4429,68	5831,15	8778,01
Fuel consumption per hour	[m^3/hr]	0,648663371	0,81070023	1,02287073	1,27641561	1,57748741	1,95768355	2,35039574	3,0610342	3,94375292	4,92186442	6,47905806	9,75334971
Fuel consumption per day	**[ton/day]**	**14,011129**	**17,511125**	**22,09401**	**27,57058**	**34,07373**	**42,28596**	**50,76855**	**66,11834**	**85,18506**	**106,3123**	**139,9477**	**210,6724**

Fig. 42: Open water resistance calculation for CV 2300 case study vessel

Resistance calculation following the procedure described in *Prediction of Resistance and Propulsion Power of Ships*(Kristensen and Lützen 2012) that is based on Guldhammer/Harvald

	Unit	Vessel data CV 4400 ICE	
			The vessel data is obtained from grosstonnage.com (grosstonnage.com 2014) or based on values from this source
LOA	[m]	294	
Lpp	[m]	281	alternative calculation using formula: LPP=0.97*LWL
CB - Block Coefficient		0,63	(MAN 2011)
T - Draught Amidship	[m]	10,78	
TEU	[TEU]	4402	
Lwl	[m]	283,81	LWL=1,01*LPP
Beam (max) - breath moulded	[m]	32,32	
Design draught	[m]	10,78	
Displacement	[kg]	63220925,28	63220,92528 [ton]
Displaced volume	[m^3]	61678,95	
Slenderness ratio - (Schlankheitsgrad)		7,18	formula: L/Displacement^(1/3) --> Graph for 7
B/T	-	3,00	
Cm-Midship coefficient	-	0,98	Kerlen (1970)
Cp - Prismatic coefficient	-	0,64	DTU p.8
Wetted surface	[m^2]	11476,93	DTU p.4
1 knot	[m/s]	0,51	
g	[m/(s^2)]	9,81	
Kinematic viscosity	[(m^2)/s]	0,00000114	0,000011883
Density saltwater	[kg/(m^3)]	1025,00	
	[t/(m^3)]	1,03	

Calculation

Speed [kn]	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Speed [m/s]		0,514	1,029	1,543	2,058	2,572	3,087	3,601	4,116	4,630	5,144	5,659	6,173
Froudes number [-]		0,010	0,019	0,029	0,039	0,049	0,058	0,068	0,078	0,088	0,097	0,107	0,117
Reynolds number [-]		128130289,7	256260579,5	384390869	512521159	640651449	768781738	896912028	1025042318	1153172608	1281302897	1409433187	1537563477
Resistance calculations													
Cf - Friction coefficient		2,01E-03	1,83E-03	1,73E-03	1,67E-03	1,62E-03	1,58E-03	1,55E-03	1,53E-03	1,50E-03	1,48E-03	1,47E-03	1,45E-03
CA - Correction scale + rough		9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05
CAA Air Resistance Coefficient		9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05
CR,Diagramm		4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04
DeltaCR,B/T		7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05
Correction Bulb		-3,50E-04	-3,41E-04	-3,31E-04	-3,21E-04	-3,11E-04	-3,02E-04	-2,92E-04	-2,82E-04	-2,72E-04	-2,63E-04	-2,53E-04	-2,43E-04
CR		1,29E-04	1,39E-04	1,49E-04	1,59E-04	1,68E-04	1,78E-04	1,88E-04	1,98E-04	2,07E-04	2,17E-04	2,27E-04	2,37E-04
CT Total resistance coefficient		2,33E-03	2,16E-03	2,07E-03	2,02E-03	1,98E-03	1,95E-03	1,93E-03	1,92E-03	1,90E-03	1,89E-03	1,89E-03	1,88E-03
RT Total resistance [N]		**3632**	**13438**	**29023**	**50250**	**77061**	**109440**	**147392**	**190937**	**240106**	**294941**	**355486**	**421793**
RT Total resistance [kN]		4	13	29	50	77	109	147	191	240	295	355	422
PE Effective (towing) Power [Watt]		1868,221178	13826,58571	44791,9878	103402,484	198219,148	337806,206	530774,799	785810,521	1111692,29	1517306,07	2011655,21	2603868,63
PE Effective (towing) Power[kW]		**2**	**14**	**45**	**103**	**198**	**338**	**531**	**786**	**1112**	**1517**	**2012**	**2604**
PEService [kW]	0	2	17	56	129	248	422	663	982	1390	1897	2515	3255

Speed [kn]	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Speed [m/s]	6,688	7,202	7,717	8,231	8,746	9,260	9,774	10,289	10,803	11,318	11,832	12,347
Froudes number [-]	0,127	0,136	0,146	0,156	0,166	0,175	0,185	0,195	0,205	0,214	0,224	0,234
Reynolds number [-]	1665693767	1793824056	1921954346	2050084636	2178214926	2306345215	2434475505	2562605795	2690736085	2818866374	2946996664	3075126954
Resistance calculations												
Cf - Friction coefficient	1,44E-03	1,43E-03	1,41E-03	1,40E-03	1,39E-03	1,38E-03	1,37E-03	1,37E-03	1,36E-03	1,35E-03	1,34E-03	1,34E-03
CA - Correction scale + rough	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05	9,56E-05
CAA Air Resistance Coefficient	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05	9,73E-05
CR,Diagramm	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	5,00E-04	5,00E-04	5,50E-04	6,00E-04
DeltaCR,B/T	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05	7,97E-05
Correction Bulb	-2,33E-04	-2,24E-04	-2,14E-04	-2,04E-04	-1,94E-04	-1,85E-04	-1,75E-04	-1,65E-04	-1,94E-04	-1,82E-04	-1,87E-04	-1,89E-04
CR	2,46E-04	2,56E-04	2,66E-04	2,76E-04	2,85E-04	2,95E-04	3,05E-04	3,15E-04	3,86E-04	3,98E-04	4,43E-04	4,91E-04
CT Total resistance coefficient	1,88E-03	1,87E-03	1,87E-03	1,87E-03	1,87E-03	1,87E-03	1,87E-03	1,87E-03	1,94E-03	1,94E-03	1,98E-03	2,02E-03
RT Total resistance [N]	**493917**	**571917**	**655853**	**745789**	**841791**	**943927**	**1052265**	**1166876**	**1329834**	**1463139**	**1630665**	**1812331**
RT Total resistance [kN]	494	572	656	746	842	944	1052	1167	1330	1463	1631	1812
PE Effective (towing) Power [Watt]	3303207,29	4119069,568	5060995,68	6138671,46	7361931,57	8740762,3	10285304	12005853,1	14366642,3	16559475,4	19294391,9	22376241,9
PE Effective (towing) Power[kW]	**3303**	**4119**	**5061**	**6139**	**7362**	**8741**	**10285**	**12006**	**14367**	**16559**	**19294**	**22376**
PEService [kW]	4129	5149	6326	7673	9202	10926	12857	15007	17958	20699	24118	27970

Propulsive Efficiencies

FA	0	
a	0,16038790	
b	0,45469395	
c	164,26085029	
w1	0,21692300	
w2	0	0 for normal N-shaped hull
w3	0,12119822	w3 <=0,1
Dprop Propeller Diameter	6,556	
wake fraction w	0,338	
d	0,151	
e	0,137	
f	-129,606	
t1	0,121	
t2	0,000	0 for normal N-shaped hull
t3	-0,034	
thrust deduction fraction t	0,087	

Hull efficiency:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
hull efficiency ηH		1,379	1,379	1,379	1,379	1,379	1,379	1,379	1,379	1,379	1,379	1,379	1,379
VA		0,340	0,681	1,021	1,362	1,702	2,043	2,383	2,724	3,064	3,405	3,745	4,086
Propeller efficiency ηO													
Cth thrust loading coefficient		1,984	1,835	1,762	1,716	1,684	1,661	1,643	1,630	1,619	1,611	1,605	1,600
ηO		0,574	0,584	0,590	0,594	0,596	0,598	0,599	0,601	0,601	0,602	0,603	0,603
		0,650	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**
ηR		1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
ηS		0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980
ηT		0,878	0,878	0,878	0,878	0,878	0,878	0,878	0,878	0,878	0,878	0,878	0,878
--> adopted ηT due to the uncertainties of the calculation for big ships like the Sofie Maersk													
Pp Propulsion Power [kW]		2,659	19,678	63,749	147,165	282,111	480,775	755,413	1118,387	1582,191	2159,472	2863,044	3705,898

Calculation is continued on next page ...

... Calculation continued from previous page.

	13	14	15	16	17	18	19	20	21	22	23	24
hull efficiency ηH	1,379	1,379	1,379	1,379	1,379	1,379	1,379	1,379	1,379	1,379	1,379	1,379
VA	4,426	4,767	5,107	5,448	5,788	6,129	6,469	6,810	7,150	7,491	7,831	8,172
Propeller efficiency ηO												
Cth thrust loading coefficient	1,597	1,594	1,592	1,592	1,591	1,592	1,592	1,594	1,647	1,651	1,684	1,719
ηO	0,603	0,603	0,604	0,604	0,604	0,604	0,604	0,603	0,599	0,599	0,596	0,593
	0,650	**0,650**	**0,650**									
ηR	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
ηS	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980
ηT	0,878	0,878	0,878	0,878	0,878	0,878	0,878	0,878	0,878	0,878	0,878	0,878
--> adopted ηT due to the uncertainties of												
the calculation --> formula only optimized for certain ship sizes												
Pp Propulsion Power [kW]	4701,217	5862,374	7202,950	8736,728	10477,706	12440,096	14638,331	17087,064	20447,005	23567,906	27460,315	31846,490

Electrical Power Consumption:			
Number of refeers:		0	
Power per refeer incl. Vent	[kW]	8,15	
Power consumption for refeers:	[kW]	0	
Auxiliary	[kW]	1700	Man-B&W 3 x 8L27/38, 4 Stroke 8Cy.
Total:	[kW]	1700	
additional fuel consumption per day	[kg/day]	7344	
	[ton/day]	7,344	
specific fuel consumption	[g/kWh]	180	Calculation with fixed specific fuel consumption
Fuel oil density	[kg/m^3]	900	

	0	1	2	3	4	5	6	7	8	9	10	11	12
Time needed to produce 1 kWh [s]		1353,94	182,94	56,47	24,46	12,76	7,49	4,77	3,22	2,28	1,67	1,26	0,97
Fuel consumption per second [g/s]		0,13	0,98	3,19	7,36	14,11	24,04	37,77	55,92	79,11	107,97	143,15	185,29
Fuel consumption per hour [g/hr]		478,60	3542,11	11474,86	26489,75	50779,98	86539,53	135974,42	201309,73	284794,45	388705,00	515347,86	667061,69
Fuel consumption per hour [kg/hr]		0,48	3,54	11,47	26,49	50,78	86,54	135,97	201,31	284,79	388,70	515,35	667,06
Fuel consumption per hour [m^3/hr]		0,000531781	0,003935676	0,01274984	0,02943306	0,0564222	0,09615504	0,15108269	0,22367748	0,31643828	0,43189444	0,57260873	0,74117965
Fuel consumption per day [ton/day]	**0**	**0,01148647**	**0,0850106**	**0,275397**	**0,635754**	**1,21872**	**2,076949**	**3,263386**	**4,831434**	**6,835067**	**9,32892**	**12,36835**	**16,00948**

	13	14	15	16	17	18	19	20	21	22	23	24
Time needed to produce 1 kWh [s]	0,77	0,61	0,50	0,41	0,34	0,29	0,25	0,21	0,18	0,15	0,13	0,11
Fuel consumption per second [g/s]	235,06	293,12	360,15	436,84	523,89	622,00	731,92	854,35	1022,35	1178,40	1373,02	1592,32
Fuel consumption per hour [g/hr]	846218,97	1055227,39	1296530,97	1572611,04	1885987,05	2239217,29	2634899,53	3075671,54	3680460,90	4242223,09	4942856,75	5732368,20
Fuel consumption per hour [kg/hr]	846,22	1055,23	1296,53	1572,61	1885,99	2239,22	2634,90	3075,67	3680,46	4242,22	4942,86	5732,37
Fuel consumption per hour [m^3/hr]	0,940243301	1,17247488	1,44058997	1,7473456	2,09554116	2,48801921	2,92766615	3,41741282	4,089401	4,71358122	5,49206306	6,36929799
Fuel consumption per day [ton/day]	**20,3092553**	**25,325457**	**31,11674**	**37,74266**	**45,26369**	**53,74121**	**63,23759**	**73,81612**	**88,33106**	**101,8134**	**118,6286**	**137,5768**

Fig. 43: Open water resistance calculation for CV 4400 ICE case study vessel

Resistance calculation following the procedure described in *Prediction of Resistance and Propulsion Power of Ships*(Kristensen and Lützen 2012) that is based on Guldhammer/Harvald

	Unit	Vessel data CV 8160	
			The vessel data is obtained from Maersk (Mærsk A/S 2014) and grosstonnage.com (grosstonnage.com 2014) or based on values from these sourc
LOA	[m]	346,98	
Lpp	[m]	331,54	alternative calculation using formula: LPP=0.97*LWL
CB - Block Coefficient		0,65	(MAN 2011)
T - Draught Amidship	[m]	14,94	
TEU	[TEU]	8160	(http://www.maerskfleet.com)
Lwl	[m]	334,86	LWL=1,01*LPP
Beam (max) - breath moulded	[m]	42,80	
Design draught	[m]	14,94	
Displacement	[kg]	141243191,32	141243,1913 [ton]
Displaced volume	[m^3]	137798,24	
Slenderness ratio - (Schlankheitsgrad)		6,48	formula: L/Displacement^(1/3) --> Graph for 6.5
B/T	-	2,86	
Cm-Midship coefficient	-	0,98	Kerlen (1970)
Cp - Prismatic coefficient	-	0,66	DTU p.8
Wetted surface	[m^2]	18635,00	DTU p.4
1 knot	[m/s]	0,51	
g	[m/(s^2)]	9,81	
Kinematic viscosity	[(m^2)/s]	0,00000114	
Density saltwater	[kg/(m^3)]	1025,00	
	[t/(m^3)]	1,03	

Calculation

Speed [kn]	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Speed [m/s]		0,514	1,029	1,543	2,058	2,572	3,087	3,601	4,116	4,630	5,144	5,659	6,173
Froudes number [-]		0,009	0,018	0,027	0,036	0,045	0,054	0,063	0,072	0,081	0,090	0,099	0,108
Reynolds number [-]		151175502,7	302351005,4	453526508	604702011	755877514	907053016	1058228519	1209404022	1360579524	1511755027	1662930530	1814106033
Resistance calculations													
Cf - Friction coefficient		1,96E-03	1,79E-03	1,69E-03	1,63E-03	1,59E-03	1,55E-03	1,52E-03	1,50E-03	1,47E-03	1,46E-03	1,44E-03	1,42E-03
CA - Correction scale + rough		-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05
CAA Air Resistance Coefficient		9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05
CR,Diagramm		4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04
DeltaCR,B/T		5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05
Correction Bulb		-3,51E-04	-3,42E-04	-3,33E-04	-3,24E-04	-3,15E-04	-3,06E-04	-2,97E-04	-2,88E-04	-2,79E-04	-2,70E-04	-2,61E-04	-2,52E-04
CR		1,07E-04	1,16E-04	1,25E-04	1,34E-04	1,43E-04	1,52E-04	1,61E-04	1,70E-04	1,79E-04	1,88E-04	1,97E-04	2,06E-04
CT Total resistance coefficient		2,09E-03	1,92E-03	1,84E-03	1,79E-03	1,75E-03	1,72E-03	1,70E-03	1,69E-03	1,68E-03	1,67E-03	1,66E-03	1,65E-03
RT Total resistance [N]		**5292**	**19457**	**41861**	**72283**	**110626**	**156854**	**210967**	**272991**	**342967**	**420952**	**507010**	**601214**
RT Total resistance [kN]		5	19	42	72	111	157	211	273	343	421	507	601
PE Effective (towing) Power [Watt]		2722,408941	20018,6372	64604,7831	148741,955	284554,164	484154,642	759714,857	1123507,96	1587938,58	2165564,43	2869112,72	3711493
PE Effective (towing) Power[kW]		**3**	**20**	**65**	**149**	**285**	**484**	**760**	**1124**	**1588**	**2166**	**2869**	**3711**
PEService [kW]		3	25	81	186	356	605	950	1404	1985	2707	3586	4639

Speed [kn]	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Speed [m/s]	6,688	7,202	7,717	8,231	8,746	9,260	9,774	10,289	10,803	11,318	11,832	12,347
Froudes number [-]	0,117	0,126	0,135	0,144	0,153	0,162	0,171	0,180	0,188	0,197	0,206	0,215
Reynolds number [-]	1965281535	2116457038	2267632541	2418808043	2569983546	2721159049	2872334552	3023510054	3174685557	3325861060	3477036562	3628212065
Resistance calculations												
Cf - Friction coefficient	1,41E-03	1,40E-03	1,39E-03	1,38E-03	1,37E-03	1,36E-03	1,35E-03	1,34E-03	1,33E-03	1,33E-03	1,32E-03	1,31E-03
CA - Correction scale + rough	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05	-7,72E-05
CAA Air Resistance Coefficient	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05	9,95E-05
CR,Diagramm	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04	4,00E-04
DeltaCR,B/T	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05	5,84E-05
Correction Bulb	-2,43E-04	-2,34E-04	-2,25E-04	-2,16E-04	-2,07E-04	-1,98E-04	-1,89E-04	-1,80E-04	-1,72E-04	-1,63E-04	-1,54E-04	-1,45E-04
CR	2,15E-04	2,24E-04	2,33E-04	2,42E-04	2,51E-04	2,60E-04	2,69E-04	2,78E-04	2,87E-04	2,96E-04	3,05E-04	3,14E-04
CT Total resistance coefficient	1,65E-03	1,64E-03	1,64E-03	1,64E-03	1,64E-03	1,64E-03	1,64E-03	1,64E-03	1,64E-03	1,64E-03	1,65E-03	1,65E-03
RT Total resistance [N]	**703643**	**814382**	**933520**	**1061149**	**1197366**	**1342269**	**1495959**	**1658540**	**1830118**	**2010799**	**2200692**	**2399907**
RT Total resistance [kN]	704	814	934	1061	1197	1342	1496	1659	1830	2011	2201	2400
PE Effective (towing) Power [Watt]	4705807,438	5865359,244	7203659,73	8734434,23	10471627,2	12429406,6	14622167,8	17064536,8	19771373,5	22757774	26039073,3	29630847,4
PE Effective (towing) Power[kW]	**4706**	**5865**	**7204**	**8734**	**10472**	**12429**	**14622**	**17065**	**19771**	**22758**	**26039**	**29631**
PEService [kW]	5882	7332	9005	10918	13090	15537	18278	21331	24714	28447	32549	37039

Propulsive Efficiencies		
FA	0	
a	0,16178164	
b	0,45539082	
c	133,61030431	
w1	0,24027627	
w2	0	0 for normal N-shaped hull
w3	0,07786101	w3 <=0,1
Dprop Propeller Diameter	9,148	
wake fraction w	0,318	
d	0,160	
e	0,133	
f	-173,558	
t1	0,134	
t2	0,000	0 for normal N-shaped hull
t3	-0,025	
thrust deduction fraction t	0,109	

Hull efficiency:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
hull efficiency ηH		1,307	1,307	1,307	1,307	1,307	1,307	1,307	1,307	1,307	1,307	1,307	1,307
VA		0,351	0,702	1,052	1,403	1,754	2,105	2,455	2,806	3,157	3,508	3,859	4,209
Propeller efficiency ηO													
Cth thrust loading coefficient		1,433	1,317	1,260	1,224	1,198	1,180	1,166	1,155	1,147	1,140	1,135	1,131
ηO		0,617	0,628	0,633	0,637	0,639	0,641	0,642	0,643	0,644	0,645	0,645	0,646
		0,650	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**	**0,650**
ηR		1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
ηS		0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980
ηT		0,832	0,832	0,832	0,832	0,832	0,832	0,832	0,832	0,832	0,832	0,832	0,832
--> adopted ηT due to the uncertainties of the calculation --> formula only optimized for certain ship sizes		**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**
Pp Propulsion Power		4,861	35,748	115,366	265,611	508,132	864,562	1356,634	2006,264	2835,605	3867,079	5123,416	6627,666

Calculation is continued on next page ...

... Calculation continued from previous page.

	13	14	15	16	17	18	19	20	21	22	23	24
hull efficiency η_H	1,307	1,307	1,307	1,307	1,307	1,307	1,307	1,307	1,307	1,307	1,307	1,307
VA	4,560	4,911	5,262	5,612	5,963	6,314	6,665	7,016	7,366	7,717	8,068	8,419
Propeller efficiency η_O												
Cth thrust loading coefficient	1,128	1,125	1,124	1,123	1,122	1,122	1,122	1,123	1,124	1,125	1,127	1,128
η_O	0,646	0,646	0,646	0,647	0,647	0,647	0,647	0,647	0,646	0,646	0,646	0,646
	0,650	**0,650**	**0,650**									
η_R	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
η_S	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980	0,980
η_T	0,832	0,832	0,832	0,832	0,832	0,832	0,832	0,832	0,832	0,832	0,832	0,832
--> adopted η_T due to the uncertainties of the calculation for big ships like the Sofie Maersk	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**	**0,700**
Pp Propulsion Power	8403,228	10473,856	12863,678	15597,204	18699,334	22195,369	26111,014	30472,387	35306,024	40638,882	46498,345	52912,228

Electrical Power Consumption:			
Number of refeers:		0	Comment: This function is optional and not used for the case study
Power per refeer incl. Vent	[kW]	10	
Power consumption for refeers:	[kW]	0	
Auxiliary	[kW]	5100	5 x 3,000kW 6,600V 60Hz Assumption: 2 auxiliary generators running at 85 %
Total:	[kW]	5100	
additional fuel consumption per day	[kg/day]	22032	
	[ton/day]	22,032	
specific fuel consumption [g/kWh]	[g/kWh]	180	Calculation with fixed specific fuel consumption
Fuel oil density [kg/m^3]	[kg/m^3]	900	

	0	1	2	3	4	5	6	7	8	9	10	11	12
Time needed to produce 1 kWh [s]		740,52	100,71	31,21	13,55	7,08	4,16	2,65	1,79	1,27	0,93	0,70	0,54
Fuel consumption per second [g/s]		0,24	1,79	5,77	13,28	25,41	43,23	67,83	100,31	141,78	193,35	256,17	331,38
Fuel consumption per hour [g/hr]		875,06	6434,56	20765,82	47809,91	91463,84	155621,13	244194,06	361127,56	510408,83	696074,28	922214,80	1192979,89
Fuel consumption per hour [kg/hr]		0,88	6,43	20,77	47,81	91,46	155,62	244,19	361,13	510,41	696,07	922,21	1192,98
Fuel consumption per hour [m^3/hr]		0,000972289	0,007149513	0,02307314	0,05312213	0,10162649	0,17291237	0,27132673	0,40125284	0,56712092	0,77341587	1,02468311	1,32553322
Fuel consumption per day [ton/day]	**0**	**0,02100144**	**0,1544295**	**0,49838**	**1,147438**	**2,195132**	**3,734907**	**5,860657**	**8,667061**	**12,24981**	**16,70578**	**22,13316**	**28,63152**

	13	14	15	16	17	18	19	20	21	22	23	24
Time needed to produce 1 kWh [s]	0,43	0,34	0,28	0,23	0,19	0,16	0,14	0,12	0,10	0,09	0,08	0,07
Fuel consumption per second [g/s]	420,16	523,69	643,18	779,86	934,97	1109,77	1305,55	1523,62	1765,30	2031,94	2324,92	2645,61
Fuel consumption per hour [g/hr]	1512580,96	1885294,04	2315462,06	2807496,72	3365880,17	3995166,41	4699982,51	5485029,70	6355084,34	7314998,78	8369702,13	9524200,95
Fuel consumption per hour [kg/hr]	1512,58	1885,29	2315,46	2807,50	3365,88	3995,17	4699,98	5485,03	6355,08	7315,00	8369,70	9524,20
Fuel consumption per hour [m^3/hr]	1,680645514	2,094771159	2,57273562	3,1194408	3,73986686	4,43907379	5,22220279	6,09447744	7,06120482	8,12777642	9,29966904	10,5824455
Fuel consumption per day [ton/day]	**36,30194309**	**45,247057**	**55,57109**	**67,37992**	**80,78112**	**95,88399**	**112,7996**	**131,6407**	**152,522**	**175,56**	**200,8729**	**228,5808**

Fig. 44: Open water resistance calculation for CV 8160 case study vessel