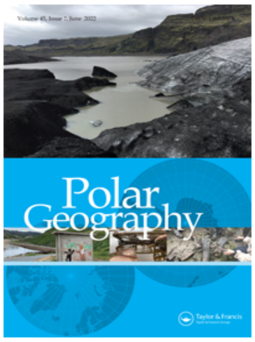

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# Arctic supply chain reliability in Baffin Bay and Greenland

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**ABSTRACT**
Despite the obvious economic advantages of utilising supply chains across the northern routes, there are significant challenges to their reliability. Every year an increasing number of ships venture into the region to supply, extract or transit the most northern parts of the world. However, supply chain reliability has been a significant challenge for ship operators, despite technological and organisational innovations. This paper investigates the hazards that face Arctic supply chain reliability in the region surrounding Baffin Bay and Greenland as well as the technological and organisational developments that are adopted to mitigate them. A bow-tie approach is used to illustrate the challenges faced by the shipping industry. We conclude that increased traffic will require significant investments in systems and infrastructure developments to manage Arctic hazards, thereby increasing reliability. Specifically, protective barriers like emergency response and icebreaker capacity need to be upgraded and positioned closer to emerging shipping lanes. Northwest Canada and Greenland are both poorly covered in terms of helicopter search and rescue and icebreaker availability. The consequence is that, with the increase in traffic outside the traditional busy routes in the south, supply chains lack access to effective Arctic hazard barriers.

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## Introduction

The exploration of natural resources (particularly minerals and hydrocarbons) has spurred renewed interest in research into the reliability of Arctic supply chains. Three research lines have emerged, focusing on the challenges faced by commercial shipping activities in the region. The first strand is primarily interested in climatological changes, aiming to include the environmental and social consequences of expanding supply chains (Fan et al., 2018; Khon et al., 2010; Meschtyb et al., 2005). The second line focuses on estimating the commercial potential of the routes for fisheries, containers and bulk and liquid cargo (Buixadé Farré et al., 2014; Gudmestad & Bai, 2020; Lasserre & Pelletier, 2011; Liu & Kronbak, 2010; Schøyen & Bråthen, 2011; Verny & Grigentin, 2009). Finally, the third line is interested in sea ice prediction, satellite coverage and navigation in the northern sea routes, all with a firm goal of developing ship construction, ice classification and

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navigational aids (Erikstad & Ehlers, 2012; Pelaudeix & Basse, 2017; Stephenson et al., 2014). All three have had significant impacts on commercial activities and have influenced approaches to industrial development.

There is, however, a need to investigate a fourth strand, focusing on achieving improved reliability using technological innovations, improvements to safety and possible solutions that affect supply chain (SC) activities in the Arctic north. The initial work has already begun, investigating safety and risk management aspects, but these systems need further development to accommodate the unique Arctic context (Ghosh & Rubly, 2015; International Maritime Organization, 2017; Panahi et al., 2020; Zhang et al., 2020). The integration of new technologies will also have to be more widespread if there is a further expansion of commercial activities in the Arctic north. Such development is needed not only when it comes to the northern sea routes (Buixadé Farré et al., 2014; Lasserre & Pelletier, 2011; Panahi et al., 2020), but also in support of industrial development, specifically regarding the extractive industry and tourism (Avango et al., 2014; Jørgsen, 2014; O'Garra, 2017). Sustainable economic development in the region will depend on at least two factors related to Arctic hazards impacting SC reliability: first, access to commercial sites and ports, which could be hindered, thereby impacting SCs (Elyakova et al., 2019; Litovkin, 2020; Lubbad et al., 2016), and, second, the role and development of emergency preparedness and the availability of icebreaker capacity to support efforts to achieve SC reliability (Dalaklis et al., 2018; Marchenko et al., 2018). With these factors in mind, this paper contributes to the literature on commercial shipping in the Arctic by improving our understanding of current SC hazards and possible mitigation.

Operations in the Arctic are a complicated endeavour, involving command, control and coordination structures both internally and between the Arctic nations (Andreassen et al., 2019). The combination of long distances, lack of infrastructure, limited navigational information and frequent harsh weather events makes operations a challenging task. The same risks influence commercial development in the region due to the complexity of coordination, the lack of communication infrastructure, uncertain bathymetric data and local sea ice conditions which can change within hours or days. SC management has traditionally focused on creating systems and implementing technology to ensure the timely and reliable transfer of goods from one location to another. With climate change making the Arctic more accessible and increasingly commercially viable, ensuring reliability and planning logistics are becoming increasingly important. With these factors in mind, we seek to answer the research question: What hazards face Arctic supply chain reliability in the region surrounding Baffin Bay and Greenland, and what technological and organisational developments are adopted to mitigate these?

This paper is structured as follows. It begins with a theoretical review, structured around the bow-tie model, focused on the research carried out on SCs, risks and challenges related to reliability, followed by a section focusing on risks and challenges specifically related to the Arctic. These sections are followed by a description of the methodology, using Arctic maritime activities to illustrate the hazards faced by commercial activities in the region. Using the bow-tie approach, we analyse cases of SC risks in Baffin Bay and the waters surrounding Greenland using examples from community supply vessels, transit traffic, bulk carriers and tanker ships in the region. The last section answers the research question and debates the findings regarding increased accessibility to the Arctic.

## Theory

Supply chain management is the coordination of activities between interdependent organisations, defined as ‘the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole’ (Jüttner, 2005). It has less to do with the needs of an individual organisation within a given SC, than with the management of the network of interdependent entities that are dependent on the reliability and quality of the means of transport that binds them together, transcending national borders and the coordination capability of a single entity. Applying a network perspective to SC in the Arctic provides a good vantage point from which to understand the complexity faced by companies, organisations and governments when working to ensure a reliable and safe environment.

The management of SC risks has traditionally been concerned with managing context-specific hazards and aims to ensure the integrity of the network. It identifies and assesses the likelihood that these hazards will occur. In general, risk assessment involves three steps: risk identification, risk analysis and risk evaluation, the last part of which can be broken down further into management, implementation and planning (Ganguly & Guin, 2007; The International Organization for Standardization, 2009). Using this structure becomes an enormous task when SCs involve hundreds of nodes and possibly thousands of individual connections. Hence, SC risk management has been moving towards identifying ‘unexpected deviations from the norm and their negative consequences’ (Svensson, 2002). In a globalised world with interconnected SC networks spanning the globe, vulnerabilities can remain unseen to individual decision-makers and make it challenging to identify and manage risks (Zsidisin & Henke, 2019). In this interpretation, a supply network is a (semi)-autonomous organisation that makes decisions independently but engenders effects within the network as a whole that are beyond their cognitive recognition.

Risk in a SC centres around the disruption of flows between organisations. These flows relate to information, resources, products and finances. We define information as the flow of data such as orders, billing, schedules and supply orders to and from the individual nodes. Resources are the ingredients, people and materials needed to maintain the SC under normal circumstances. Products are the goods moving between nodes within the SC, and, finally, the flow of finances is the funds that move through the system to ensure system integrity. In this way, the nodes are interdependent and connected, even though individual entities do not recognise all the nodes contributing to the network. Utilising this approach encompasses complexity, providing SCs with the ability to cope with the consequences of changes from the norm and subsequently to return to their original state or, even better, an improved reliability level.

When analysing SC risks, we look for events that affect the flow of information, resources, products or finances (Zsidisin & Henke, 2019). To protect and prevent events from impacting these flows, organisations implement preventive barriers, which are organisational technologies that prevent or mitigate a hazard from turning into a risk event. If an event should materialise, organisations have protective barriers that will prevent or minimise unwanted consequences (Hopkin, 2018). The bow-tie model (Figure 1) describes the relationship between causes and consequences of an event. The model consists of a fault tree on the left side and an event tree on the right, centred on an event. The causes are indicated on the left and consequences on the right side. The causes are the sting of individual incidents that might lead to an event, and the consequences are losses when the event

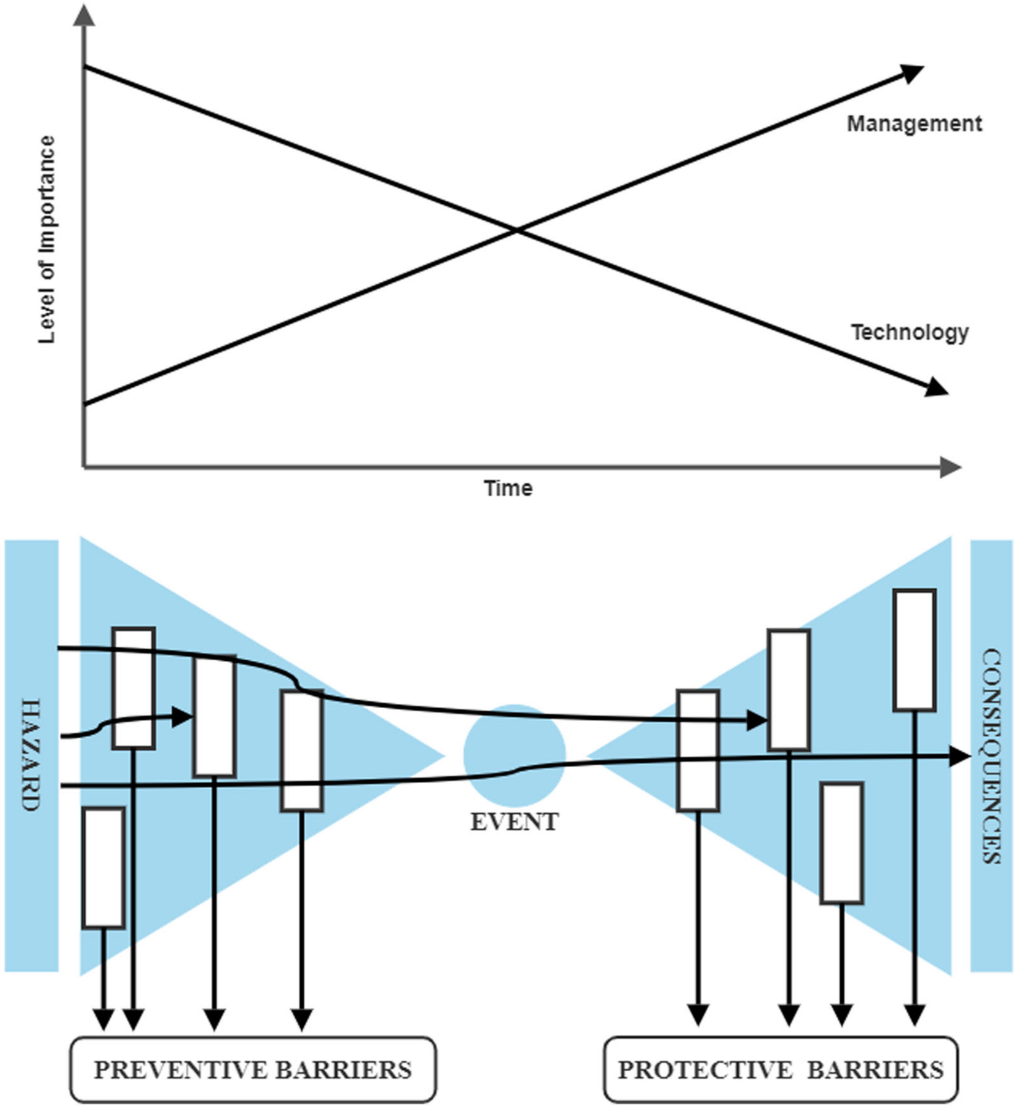

**Figure 1.** The bowtie model depicting the level of importance of management and technology on safety (authors' own creation).

is realised. To prevent a hazard from negatively impacting the organisation is a series of preventive and protective barriers erected that will prevent hazards or mitigate their impact. These barriers can be technical, for example, improvements to ship design or organisational, such as risk management systems. On the top left side, how technology plays a role in the effectiveness of preventive barriers and, on the top right side, how organisational risk management capabilities and resource coordination become increasingly important to prevent an event, should it happen, from having negative consequences.

In line with our network understanding, a resilience-based perspective on SC risk focuses on the adaptive capacity to deal with temporary changes from the norm (Anbumozhi et al., 2020). These changes imply uncertainty in the SC regarding producing the desired output, threatening current operations (Zsidisin & Henke, 2019). The adaptive capacity to be resilient is an organisation's ability to be responsive, monitor, learn and anticipate changes in the environment, using a combination of technology and management (Hollnagel et al., 2015; Taarup-Esbensen, 2020). While there are variations, the definitions share the perspective that resilience means responding to and recovering from changes, using continuous learning to improve the overall system's ability to cope with future changes.

## *Arctic SC risks*

Managing SC hazards in the Arctic focuses on two parameters that will ensure greater integrity of the system and improve reliability. Identifying the right balance between introducing new technology and effective management makes the overall system resilient, thereby ensuring that, should one connection fail, there will continue to be alternative ways to ensure its integrity. For example, preventive initiatives can come in the form of technology such as ice class ships, improvements made to harbours and better satellite and navigational tools. Protective barriers can come in the form of improvements to emergency response coordination, assistance from icebreaker ships and the capabilities needed to ensure business recovery when unwanted events do materialise.

In the Arctic context, there are different types of SC risks to consider. The region is exposed to many risks similar to those encountered in other areas, as well as particular and unique types of hazards. Changes to information, resources, products and finance flows are at the centre of SC risk analysis, and the aim is to provide reliability to the system. Table 1 below describes examples of Arctic hazards that can affect the reliability of an SC network (Afenyo et al., 2020; Det Norske Veritas, 2019; Emmerson & Lahn, 2012; Marken et al., 2015; Smits et al., 2017; Taarup-Esbensen, 2019; Zhang et al., 2020). The hazards have been categorised into four themes: technical, safety, environmental and reputational. Technological hazards are changes in the environment that impact a ship's ability to manoeuvre and maintain structural integrity under Arctic conditions. Operational hazards focus on navigation and the ability to communicate efficiently with the outside

**Table 1.** Arctic hazards that can affect the reliability of an SC network.

| Technical hazards | Safety hazards | Environmental hazards | Reputational hazards |
|---|---|---|---|
| • Polar lows, strong winds, heavy snowfall effect on equipment efficency<br>• Darkness effect on navigation on land and sea<br>• Uncertain metocean data<br>• Sea ice and icebergs' effect on navigation<br>• Marine and atmospheric icing on vessels and machinery<br>• Power loss due to mechanical failure<br>• Uncertainty due to lack of accurate weather information<br>• Reduced satellite coverage latitude<br>• - Remoteness and lack of infrastructure, emergency response and logistics | • Fire on both land and sea<br>• Severe weather<br>• Lack of IT and phone communication<br>• Health and safety (work environment)<br>• Qualifications and competencies of personnel<br>• Language barriers internally within the organisation and with external partners<br>• Avalanche/tsunami events<br>• Airborne diseases (for example COVID-19) | • Hazardous materials/ chemical spills' effect on local environment<br>• The remoteness or lack of emergency response equipment | • Breach of rules set by authorities<br>• Effect of pollution on the maritime environment<br>• The response does not meet stakeholder expectations |

world. Safety hazards have to do with crews' health and safety and the coordination of an effective rescue response. Environmental hazards concern the impact a given catastrophic event can have on the fragile Arctic environment and mustering an adequate response. Lastly, reputational hazards focus on how organisations maintain legitimacy with stakeholders and thereby their legal and social licence to operate.

Building resilient SCs in the Arctic, which involves multiple uncertainties, a lack of adequate and reliable data and continual changes to the context, is not an easy endeavour (Rød et al., 2016). Not surprisingly, the dominant strategy of the region's authorities is to create systems that incorporate redundancies for the most vulnerable aspects. Adopting standalone systems is an expensive strategy, which restricts funds to individual nodes and connections and creates autonomous units that function without resources from the outside world. While this approach makes the individual units robust, the whole system could still become unstable when these single semi-autonomous points are brought together into an SC network. While the singular units can withstand unexpected deviations from the norm as well as their negative consequences, the system as a whole becomes expensive and prone to failure.

## *Meeting the challenges of Arctic supply chains*

Different forms of technology have been applied to Arctic SCs to ensure access and reliability. New technologies come in the form of land-, sea – and space-based innovations, from the improvement of port facilities to the development of ice breaking capabilities that free up resources from individual ships and place some responsibility on the countries that have jurisdiction (Dalaklis et al., 2018; Knol & Arbo, 2014; Lin et al., 2020). However, there continues to be significant gaps in the development of infrastructure in the Arctic. These gaps will ensure that individual shipping companies and nodes will endure extra costs when transiting or servicing Arctic communities. For example, significant parts of northern Greenland and Canadian communities are without port facilities, and goods need to be brought in by barges (Hendriksen & Hoffmann, 2016).

Eight Arctic countries – Canada, the United States of America, Russia, Denmark, Norway, Sweden, Finland and Iceland – have signed agreements supporting and helping to coordinate emergency responses in order to create more resilient SCs and protect the fragile Arctic environment (Arctic Council, 2009, 2013). The agreements state that the Arctic countries shall assist persons, vessels or other craft in distress. In 2017, an evaluation of the current response capacity noted that it is difficult to define and agree upon the right level of emergency preparedness in different areas. It is particularly difficult to verify whether the emergency preparedness in place is proportionate to the desired levels before an accident occurs. Most experts agree that current emergency response arrangements in the Arctic lack the necessary resources, and many challenges remain regarding international cooperation. Of particular concern is the Arctic cruise traffic, which involves vessels with up to several thousand persons (passengers and crew), but other industries are also identified as being at risk, like oil and gas, which is increasingly transported through the region. The general increase in traffic seen across shipping industries has arrived with the retracting sea ice and more extended periods of open water.

There are three types of SC vessels of interest that are active in the Arctic region: community supply ships, container ships transiting the region and bulk carriers and tankers. Detailed information on ship traffic in Baffin Bay is fragmented and limited yet central for planning and risk management purposes. However, some studies show that there has been an increase in cargo ship traffic starting from early 2000 (Dawson et al., 2018; Eguíluz et al., 2016). Traffic has seen a steady increase in the Canadian Arctic moving further north, as Lancaster Sound has opened up to more traffic due to a decrease in ice cover (Pizzolato et al., 2016). The impact of decreasing ice coverage on traffic numbers is debated, as it is hard to get access to accurate data. However, the changes in ice cover represent one of the most significant changes that the region has experienced within the last two decades. According to a study by Dawson et al. (2018), the total traffic in the region tripled in the period between 1990 and 2015, indicating a significant increase of interest from commercial and leisure ships. Each of these experience different challenges regarding which types of preventive and protective barriers will improve reliability and ensure higher SC resilience. Supply ships transport finished or semi-manufactured products to communities or transit the region, and can vary in size from converted shipping trawlers to specialised vessels. Bulk carriers and tankers transport raw material from extractive sites, like the Bluejay and the Mary River Mine project in the high Arctic, which we explore in this paper, typically in significant quantities. Container ships transit the region with goods from Europe, the United States and Canada to markets in Asia and back.

## Methodology

Using cases and examples from Greenland and Baffin Bay, the aim of this paper is to show how the bow-tie approach provides insights into the technological and organisational innovations that operators have implemented to improve reliability. Using the methodology, we illustrate how SC operators have experienced challenges with reliability and the actions that they have taken to overcome these in order to increase their resilience.

We use cases from three types of transport (community supply vessels, container ships and bulk carriers and tankers) to illustrate how SC risks affect the industry. We have opted to illustrate our arguments by using publicly available examples of how different risks impact industries and their ability to produce reliable and effective SCs. While these cases do not represent the full complexity of managing complex networks in the Arctic, they serve to show how companies have identified and analysed some of the central risks to their business and made decisions to mitigate these. The structure of the analysis follows the bow-tie approach, looking for the primarily technology-driven preventive barriers and the organisational protective barriers that the industries rely on to manage SC risks.

Preventive barriers are analysed using empirical examples related to the development and introduction of technology from sources of innovation developed within the shipping industry. We searched for technologies that explicitly mitigate the identified Arctic hazards (see Table 1) and incorporate them into ship designs and infrastructure development. Of specific interest is the introduction of technology that improves reliability and could mitigate technical, operational, safety, environmental and reputational hazards.

Icebreaker availability and emergency preparedness in the seas surrounding Greenland and north-eastern Canada are essential for robust protective barriers. Evidence was collected from the Greenlandic government, the Danish Arctic Command and the Canadian Coast Guard. Significant upgrades, especially of the capacity in Greenland, have meant improvements in emergency response capacity, which could impact the event management. We also investigate the availability of icebreakers as a supplement to the steps taken to improve ship design. Icebreakers act as protective barriers by supporting ships through sea ice or bergy waters (Federal State Budgetary Institution, 2021), as well as helping vessels that cannot independently break free from sea ice. The search and rescue (SAR) capability in the region provides an in-depth understanding of how efficient the response would be should an event occur, and an indicator of how governments emphasise different parts of the region as traffic increases. We also use experiences from SAR exercises conducted at 80 degrees north (Gudmestad & Solberg, 2019), leading to updates of the IMO Polar Code (International Maritime Organization, 2017).

## Analysis

Arctic SCs are complex and filled with both technical and organisational uncertainty regarding their reliability. Often, schedules only exist on paper, as changes in weather and sea ice, as well as uncertain navigation, can mean delays of days or even weeks (Marken et al., 2015). Moreover, the increase in traffic causes local communities to question major investments in their area. For example, in 2018, the mining company Ironbark sailed an ore-ship into Citronen Fjord, located at 83 degrees north in Greenland to convince investors that their zinc project was feasible (Jørgensen, 2020; Minex, 2018). The mining project contains one of the largest global zinc deposits, which would be very lucrative if extracted. However, the endeavour turned out to be unsuccessful because the ship encountered a severe sea ice build-up which it could not pass. In the end, Ironbark had to abort the effort, and, to date, no commercial ship has made it into the fjord.

Another example is the delay of a cable repair ship that resulted in the southern part of Greenland being without reliable internet. The leading cause of the delay was a combination of poor weather and organisational difficulties in hiring the ship at short notice. In the end, a large proportion of the western coast of the country was without functioning internet for close to three months (Nyhedsredaktionen, 2019; Willle, 2019). Similar challenges are witnessed on both the Canadian and Greenlandic sides, with the expansion of mine projects throughout the coastal areas causing widespread local protests (CBC, 2014; Ginac, 2020; Schultz-Nielsen, 2020; Sevunts, 2021). Projects that have been initiated, such as mining ventures, have not met local stakeholder expectations as to what effect the increase in traffic will have, causing some companies to abandon projects at risk of losing government support.

The analysis structure follows the thinking that the effective management of SC risks is performed through two components: preventive and protective barriers. The first refers to the implementation and use of technology developed for Arctic conditions and the second to an effective coordination of organisational resources.

### *Use of technology in developing effective supply chains – preventive barriers*

Innovation in Arctic shipping technology began over 200 years ago, but has developed considerably in the past 40 years due to the increase in commercial traffic in the region. Systems like the azimuth thruster and double acting ships are available, enabling improvements to ship propulsion and manoeuvrability with their rudderless movement in any horizontal direction (Buixadé Farré et al., 2014) and the ability to go stern first into the ice (Juurmaa et al., 2002). Technologies also include improvements to hull designs to deal with thick ice, including draught systems that enable the breaking of ice ridges which can extend over nine metres in thickness (Brubaker & Ragner, 2010). The majority of advances have focused on mitigating technical, operational and safety hazards, which historically have had the highest number of incidents. However, in recent years, the industry has placed more emphasis on environmental and reputational concerns, like those faced by extractive industries in both Arctic Canada and Greenland. Companies have also introduced technologies that mitigate environmental challenges, hoping that this will improve the industries' reputation. For example, some companies have reduced the consumption of traditional diesel, moving towards hybrid power, which combines liquefied natural gas (LNG), biogas (LBG) and battery packs (Lasserre et al., 2016; MAN, 2011). The estimate is that the more efficient engines will reduce $CO_2$ emissions and decrease fuel consumption by up to one quarter, compared to 2015 levels; this also represents a significant reduction in NOx emissions (The Explorer, 2020). Furthermore, a ban on the use of heavy fuel will reduce the emission of soot; this will reduce pollution and the rapid melting of the snow and ice cover (Brzozowski, 2020). The aim is for these technologies to open more of the region for commercial traffic and reduce the chances of polluting the fragile Arctic environment in the case of an event. Sea ice cover and ice drift prediction technology have also undergone great leaps, which will enable safer and improved supply chain scheduling. Satellite technology and other remote sensing are used to create more accurate maps and forecasts which operators in the region can use (Blockley & Peterson, 2018; Choi et al., 2019).

### *Advances in ship design*

These improvements in ship design and propulsion system of support vessels have made the region more accessible, at least in theory. Many of the ships operating in the region are either old or unsuitable for technological upgrades. Hence, not all who venture into the Arctic have these technologies available, and the improvements represent significant investments for the individual companies. For example, Royal Arctic Line operates vessels built in the early 1980s, while Desgagnés in Canada operates a fleet whose oldest ships are from the mid-1990s (Desgagnés, 2021; Royal Arctic Line, 2020a). Furthermore, small fishing or cargo operators with ageing fleets do not necessarily have access to commercially available technology. In practice, this means that most of the ships operating in the region are either using outdated technology or only partially implementing the best possible solutions. In a bow-tie context, the interpretation is that preventive barriers are less efficient, and the possibility of an event increases as the traffic increases.

Community supply vessels are smaller container ships operating between the major cities in the region and smaller settlements or natural resource projects. They can vary in size and capabilities, such as trawler-size ships, like Anguteq Ittuk, which, together with her sister ships, serves the communities along the west Greenlandic coast (Royal Arctic Line, 2020a). Some vessels have an ice class, while other smaller boats in the fleet, like settlement feeder ships, do not have these capabilities. Larger ships like the Irena Arctic have ice class A1, conducting operations between larger settlements and cities. The ships can navigate difficult ice conditions without icebreaker assistance (Det Norske Veritas, 2016; Royal Arctic Line, 2020b). The recent purchase of the Tukuma Arctica, with an ice class of A1 super, which operates in the Atlantic between Denmark, Iceland, the Faroe Islands and Greenland with a capacity of 2,150 containers, improves the Greenlandic primary supply chain significantly (Royal Arctic Line, 2020b). Communities witness recurring delays and disruptions to planned schedules, such as when the containership Malik Arctica tried to enter the harbour at Ittoqqortoormiit (Scorsbysund) but got trapped in ice (Figure 2). After a week, the ship had to return to Reykjavik, taking another week before it could

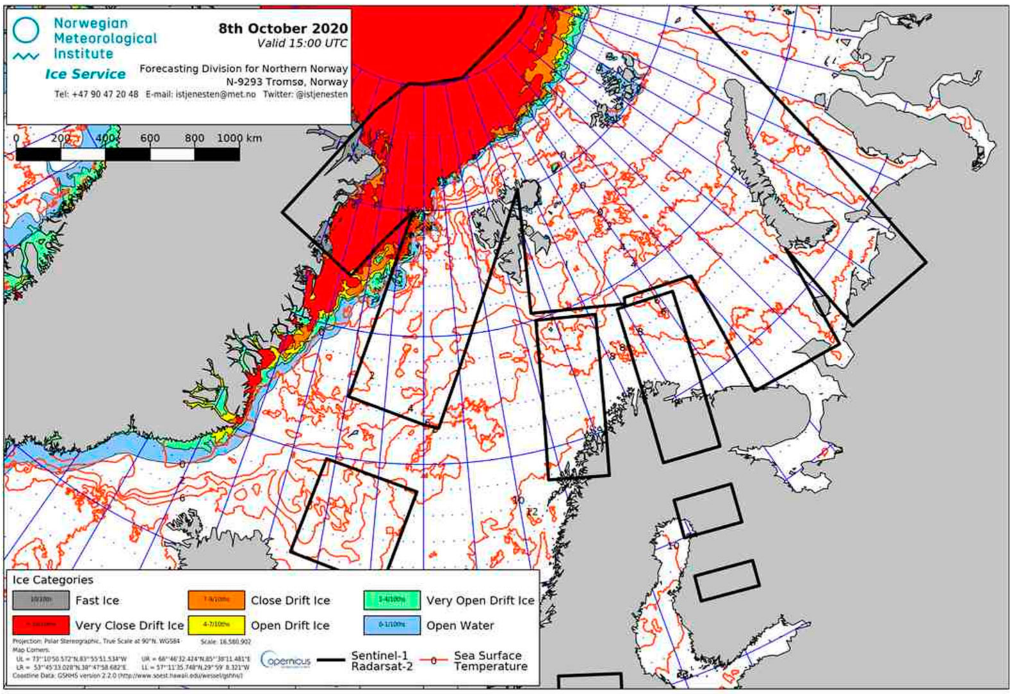

**Figure 2.** Ice conditions on October 8, 2020, (courtesy of the Norwegian Meteorological Institute, 2020). Ittoqqortoormiit (Scorsbysund) is located at the southern boundary of the Very Close Drift Ice.

finally supply the town with barges (Nyhedsredaktionen, 2019; Veirum, 2020). With the current technology in place, the community SC is vulnerable as regards reliability. While new technology is finding its way, it would seem that, despite efforts to create more efficient preventive barriers, they do not effectively target SC hazards when serving communities with supplies. The Royal Arctic Line saw an unusually high average of SC performance in 2019 of around 90%, attributed to the excellent weather conditions, fewer accidents and improved sailing planning, which bypassed areas of strong winds (Royal Arctic Line, 2019). However, there continues to be some SC disruptions regarding these types of services. While the fleet is being upgraded with newer and more ice-capable ships, there continues to be a need for the planning and management of events when they occur.

### *Infrastructure development*

Transiting ships are not immune to the hazards faced in the local routes. There is some way to go before the Northwest Passage can represent a feasible alternative to the route through the Panama Canal, despite using the latest ice class ships and help from icebreakers. Even though it is possible to travel the Arctic passage, it continues to be a challenging journey. Current technology, like improvements in fuel efficiency, ice class and the use of more efficient icebreakers, has yet to make the passage economically feasible for commercial shipping.

Arriving later than scheduled at a major container port represents a significant financial concern, with long waiting times until a new slot for offloading becomes available. It may be necessary to book slots in the container harbour, allowing for possible delays because of difficult sailing conditions, thereby increasing transport costs (Marcus M. Keupp, 2015). Therefore, it would be possible to make savings if reliability through the Northwest Passage could be increased, where there is currently a high likelihood of delays (Giguère et al., 2017; Marken et al., 2015). It should be noted that the traffic numbers are relatively low, as 2019 marked what is considered a busy shipping season in the Canadian Arctic, with 27 ships making a full transit through the Northwest Passage. This is a lower count than ships passing through the Northeastern Sea Route (NSR), where the number was 37 for the same year (Center for High North Logistics, 2020; Federal Agency for Maritime River and Transport, 2020; Sevunts, 2019). The total number of full transits through the Northwest Passage in 2019 was fewer than in 2017, which saw 31 transits compared to the five full transits in 2018. 2019 saw a marked increase in commercial traffic through the passage, with five general cargo ships and an equal number of passenger ships making a full transiting.

Technological advances have increased access through the Northwest Passage for transport of mineral ores from Greenland or Baffin Bay to the East-Asia market. However, there are significant differences in the effectiveness of these technologies to mitigate risks. Ice class ships can traverse ice, like the ICE-1A super, which is the highest class capable of navigating in difficult ice conditions without the assistance of icebreakers, but can only travel through ice of up to one metre (Det Norske Veritas, 2016). These limitations place significant restrictions on the utilisation of transit shipping through the Northwest Passage. Using icebreakers is expensive and due to the slow speed is not as fast as one might expect, looking at the distances travelled, making competition with the Panama Canal less viable.

A growing number of ships service the many extractive companies that operate in the Arctic region. There is a vital SC link between production companies and their suppliers and customers. Natural resource extraction is on the rise, and the need for improvements to both capacity and SC reliability is becoming urgent. Serious efforts to develop mining projects in the northern parts of Greenland are underway, with up to ten projects planned to be realised within the next five to seven years (Dansk Industri, 2018). They are dependent on the ability of bulk carriers to service harbours close to the extractive sites, as the use of barges is seen as an unrealistic option for most of these companies. For example, Bluejay Mining Company has initiated the Dundas Ilmenite Project, located in the north-western part of Greenland. The company is planning to extract ilmenite from a 30-kilometre-long and 2-kilometre-wide beach, around 80 kilometres south of the settlement of Qaarnaq mentioned earlier. The project entails building a harbour which is to be serviced between 10 and 12 times a year (Figure 3).

The increase in traffic should be compared to the two planned annual supply ships to visit Qaarnaq, which can only make port between July and September, making the period where ore shipping can occur very short. Further, the Ironbark project in Citronen Fjord, at 83 degrees north, is planning to build a port and to ship principally zinc at least twice a year. However, it has not been easy to show investors that a project in the high north will manage SC risks primarily related to uncertain data on sea ice and the availability of ships that can make the journey (Davis, 2020; Sermitsiaq, 2018). A source of inspiration could come from innovations from new LNG carriers which have made it possible to service gas-producing terminals in the Russian Arctic. The solution promises that large quantities of LNG can be transported efficiently and reliably for most of the year without icebreaker assistance. One example in this field is the company Total, in cooperation with the Russian company Novatec, commissioning 15 LNG carriers with superior ice class capabilities

**Figure 3.** Harbour construction at Bluejay Mining in north-western Greenland (courtesy of Bluejay Mining).

(Total, 2020). The ships, 300 metres long and with a capacity of 172,600 cubic metres, can sail in temperatures as low as −52°C through ice as thick as 2.1 metres. The LNG carriers have improved hulls (ice class Arc7), making them the most prominent vessel type with ice class certification. The ships can operate sailing forwards, breaking ice of up to 1.7 metres, and, in combination with an alternative bridge, backwards, with ice breaking capabilities of up to 2.1 metres. They also carry the Azipod system, making it easier to manoeuvre through ice and dock at ports. Total operates these ships, delivering from the Yamal LNG plant in the Russian district of Yamalo-Nenets to consumers in Asia and Europe. During the winter months, with the heaviest ice conditions, the LNG is transported westwards by these tankers and transferred to traditional LNG carriers at ice-free ports for transport to the market. One word of caution is required, as icebergs and bergy bits are present almost everywhere in the Greenland and Canadian Arctic, while the NSR sees icebergs only along certain limited passages.

In both Greenland and Canada, the SC infrastructure is underdeveloped or needs an upgrade that can support current and future traffic increases (Rosing et al., 2014). While innovations in ship design will strengthen individual ships' ability to navigate the Arctic waters, there is a lack of supporting infrastructure. Greenland has invested in three new airports which are planned to be completed by 2024 (Naalakkersuisut, 2018)). However, ports and communication systems continue to lag in terms of investments. For example, Qaanaaq (established as the American Thule Base, built in 1953), at 77 degrees north (on the western coast), has two supply vessels from Royal Arctic Lines call at the end of July and September, as well as the annual call of an oil tanker (Hendriksen & Hoffmann, 2016). The supply ships and tankers call at the same connection: Siorapaluk, Qeqertat and Savissivik (all at 77 or 78 degrees north). Qaanaaq has no actual natural harbour (a civil airport is located 4 kilometres away, and the military Thule airport is located 110 kilometres away). A reef provides some shelter for smaller boats, while accessing dinghies and boats is troublesome and occurs directly via the beach. These challenges mean that even the slightest wind can make navigation difficult. Goods from the Royal Arctic Line must be barged in, just as exports of, e.g. halibut and waste, must be barged out. In the winter, tide-based sea ice coverage occurs within the reef, making it challenging to transport halibut, and, during the thawing period, the loaded sledges must be 'sailed' into ice flakes. These infrastructure challenges impact SC reliability, as hazards due to circumstances outside the control of SC operators can have consequences in other parts of the system. Innovation and the creation of preventive barriers rely not only on the technologies that can be developed to improve ship design but also on robust land-based infrastructure.

### *Managing preventive barriers*

The enormous amount of natural resources present in the Arctic region have been drivers for innovation. The example from Russia is an illustration of how demand drives technological development and the investments needed. In the Ironbark example, technologies that would solve the company's SC risk challenges are not yet available but could possibly be developed using existing technology (Sermitsiaq, 2018). Meanwhile, in the case of Total, it is the already proven business case and the demand for gas in Asia and Europe that are the lead drivers for the development of advanced ice class LNG carriers and improvements to shipping facilities. Supply chain challenges centre on the availability of adequate infrastructure. Greenland has invested in improvements to the port of Nuuk (McGwin, 2017). The infrastructure and the development of new ship types are either already in place or available within the next few years, helping the industry in the recovery process.

The preventive barriers to SC risks in the Arctic have witnessed demand-driven innovations. Bulk, oil and LNG carriers have seen substantial improvements to ship design and to land-based infrastructure. However, in sectors where the demand for Arctic-specific solutions is low, and in industries where the economic margins are tight, there is less incentive to implement existing technologies or develop unique solutions for particular industries. The reliability of SCs in the Arctic depends on investments in ice class ship designs and technologies to improve the links between nodes. The companies and communities also play a role in implementing barriers that will improve SC infrastructures, such as port facilities and communication installations. These are measures that reduce risks and prevent the most common types of hazards that evolve into events that could potentially have consequences for SC reliability. As described in the bow-tie model (Figure 1), emphasis is placed on developing technological barriers to Arctic hazards. A solution could come through the use of the Polar Code, which describes a range of minimum standards for ship design that support efforts to make SCs more reliable (International Maritime Organization, 2017). The goal of the code is to provide safe ship operation and the protection of the polar environment by addressing risks present in polar waters and not adequately mitigated by other instruments of the organisation. Hazard identification is central to effective mitigation, and the use of the Polar Code supports these efforts. These are, however, limited to challenges to technical systems, operations, safety and the environment, and do not address the reputational impacts that might emerge from an event.

## The effective coordination of organisational resources – protective barriers

Protective barriers constitute the initiatives that organisations can take, given their available resources, to mitigate the effects of an event that has taken place. While technology plays an essential role in the erection of barriers to avoid events from materialising, these do not reduce the likelihood to zero. When events occur, the contribution made by organising and response becomes more critical in mitigating or protecting the SC from experiencing consequences. The following section will explore the protective barriers aimed at Arctic hazards.

### Fog and icing

There are a series of hazards that ships are tasked with managing when sailing off the coasts of Greenland and Canada. Fog is a cause of low visibility, particularly in Baffin Bay in the spring and summer (Canadian Coast Guard, 2012; Panahi et al., 2020). Sea fog forms when warm, moist air moves over the colder seawater, and as the air cools, it condenses, forming large areas of fog, causing a potential disruption to navigation. Sea fog may persist for long periods, even under windy conditions, providing that a continuous supply of warm moist air is available. In recent years the number of icebergs near traffic lanes has increased in Baffin Bay (see Figure 6), which, in combination with fog, can lead to collisions. While barriers exist in navigation equipment and improvements to ship design, it is impossible to totally mitigate these events.

Icing is another challenge that operators will need to manage. While a less frequent phenomenon, with most areas in the high Arctic experiencing between 25–50 h annually, in areas such as western Baffin Bay, Davis Strait and the Amundsen Gulf near Cape Parry, off Brevoort and Resolution Islands in the south, icing may occur for as many as 100 h each year (Canadian Coast Guard, 2021). Icing is a challenge, as there are fewer preventive barriers available, and it is one reason why ships are lost at sea (Dehghani-Sanij et al., 2017). Sea spray is typically of more concern than freezing fog, as ice accumulation from sea spray is often more substantive. Icing conditions occur most frequently from October to December, when air temperatures typically range between freezing and −15° C and are off-season to the regular SC traffic. When air temperatures fall below −15°C, icing becomes less of an issue, as the airborne water droplets freeze before contact with a vessel (Nunavut Impact Review Board, 2018). Icing can also affect critical safety systems, such as lifeboats and rafts, which can become unavailable, or equipment can break down due to changes in material qualities in extreme cold below −40°C (Haimelin et al., 2017). Protective barriers can come in the form of improvements to forecasting, avoiding areas where icing can occur or using chemicals as an alternative to organising crewmembers to remove ice through physical means with the use of mallets, picks and shovels.

### Sea ice and icebergs

Canadian glaciers on Baffin, Bylot, Devon, Coburg and southern Ellesmere Islands calve icebergs, but only in small numbers of around 150 a year. In contrast, the total annual production of icebergs in Baffin Bay is estimated to be somewhere between 25,000 and possibly 40,000 (Nunavut Impact Review Board, 2018; Ressel et al., 2015). More than 90 percent of the icebergs come from west Greenland glaciers, specifically around and north of Disko Bay and starting from the Jakobshavn glacier (Larsen et al., 2015). A consequence of the draught of an iceberg is that ocean currents and winds strongly influence its drift relative to its area and mass and the comparative strength of each. Icebergs calved from glaciers on the west Greenland coast usually drift northwards at 5–10 kilometres per day, before being carried westwards across northern Baffin Bay (Canadian Coast Guard, 2012). Currents then carry the icebergs south to the Labrador Sea and onto Newfoundland's Grand Banks, at a drift rate of up to 15–20 kilometres per day. Whereas the main drift path in Baffin Bay is anticlockwise, it is not uncommon for icebergs to be carried westwards across the bay by smaller currents which branch off from the West Greenland current. Iceberg drift is seldom direct, with icebergs frequently following lesser currents into bays and inlets. The continuous stream of sea ice and icebergs presents a significant challenge to SC reliability. It crosses increasingly essential sea lanes and can clog up access to inlets, making it challenging to access port facilities. In 2020, the area of bergy water in the north-western part of Baffin Bay continued to expand southwards and reached just south-east of the entrance to Pond Inlet (Canadian Ice Service, 2020). At the end of June, the ice edge was east of 65° W and south of about 72°N, with only a few patches of medium and thick first-year ice to the north-west. The average increase in temperature that the region has experienced led to more bergy water reaching further south along the east coast of Nunavut. Figure 4 shows how the northern parts of Baffin Bay in June of 2020 compared to the year before. June 2019 saw less average ice (red), while the southern part witnessed an increase in sea ice (blue) (Canadian Ice Service, 2020). For example, in 2019 the ice melt was generally 1–2 weeks earlier than climatology (1981–2010). In the same year, the north-western part of Baffin Bay saw unusual conditions with changes coming six weeks earlier than normal. The exception was along the ice edge in northern Davis and south-eastern Baffin Bay, where conditions were 1–2 weeks later than normal due to colder than usual temperatures in the area. However, in 2020 with the formation of the ice bridge across the southern

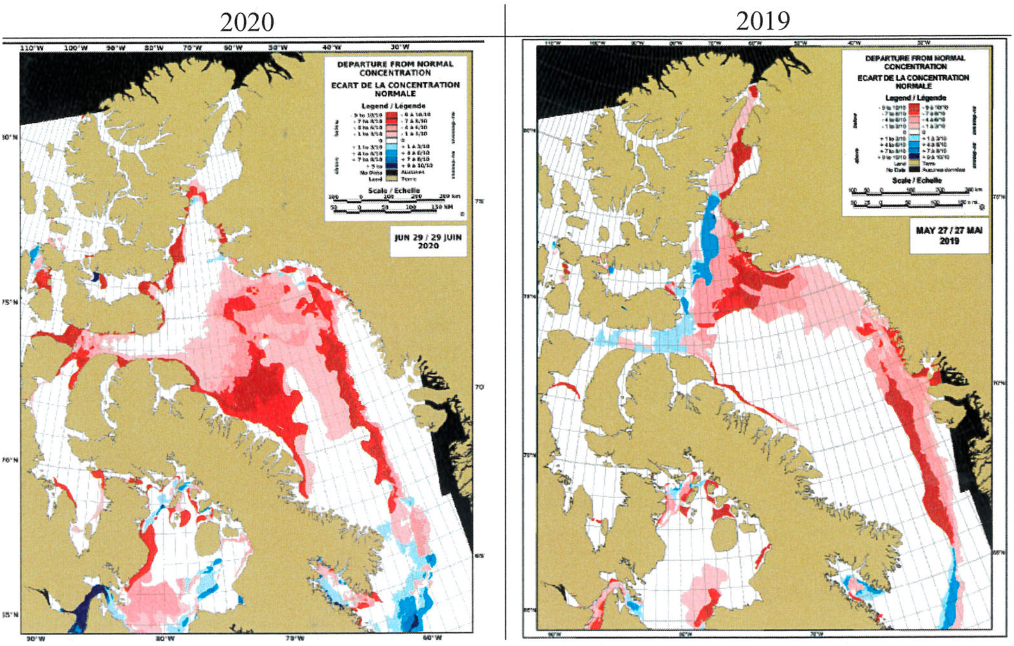

Figure 4. Departure from average ice concentration for the Eastern Arctic area, June 29, 2020 and May 27, 2019 (Courtesy of Canadian Ice Service).

part of Kane Basin during the winter, the influx of old ice from the Lincoln Sea was cut off and less old ice was seen in Baffin Bay than in 2019. The general trend is that the sea ice cover is diminishing and is highly dynamic on a year-to-year basis. This change is supported by research showing that summer sea ice cover in particular has decreased significantly across nearly all Canadian marine regions, and the rate of multi-year ice loss in the Beaufort Sea and Canadian Arctic Archipelago had nearly doubled in the period from 2010 to 2018 (Mudryk et al., 2018). The same study predicted a reduction in autumn and spring snow cover fraction and sea ice concentration of 5–10% per decade, with similar reductions in winter sea ice concentrations in both Hudson Bay and eastern Canadian waters. Figure 5 shows the weekly ice coverage for the year 2020 compared to the median from 1981 to 2010, which shows how the ice cover has diminished significantly, especially in the period from late June to September.

The change in the dynamics of sea ice means that places as far south as Newfound Island have witnessed prolonged periods of ice cover, which normally ends in early May. One study showed an abnormally thick ice cover remained present around Newfoundland after this period and was present even in June of 2017, a time of year when marine vessels normally operate unimpeded by sea ice (Barber et al., 2018). Some of this ice consisted of multi-year ice that had travelled over 3,000 kilometres from the Lincoln Sea and Canadian Arctic Archipelago to the coastal waters around Newfoundland within one ice season, a journey taking it down the whole length of Greenland. The transition towards an increase in the export of multi-year ice is accelerating the transition towards a younger and thinner Arctic ice pack (Moore et al., 2021).

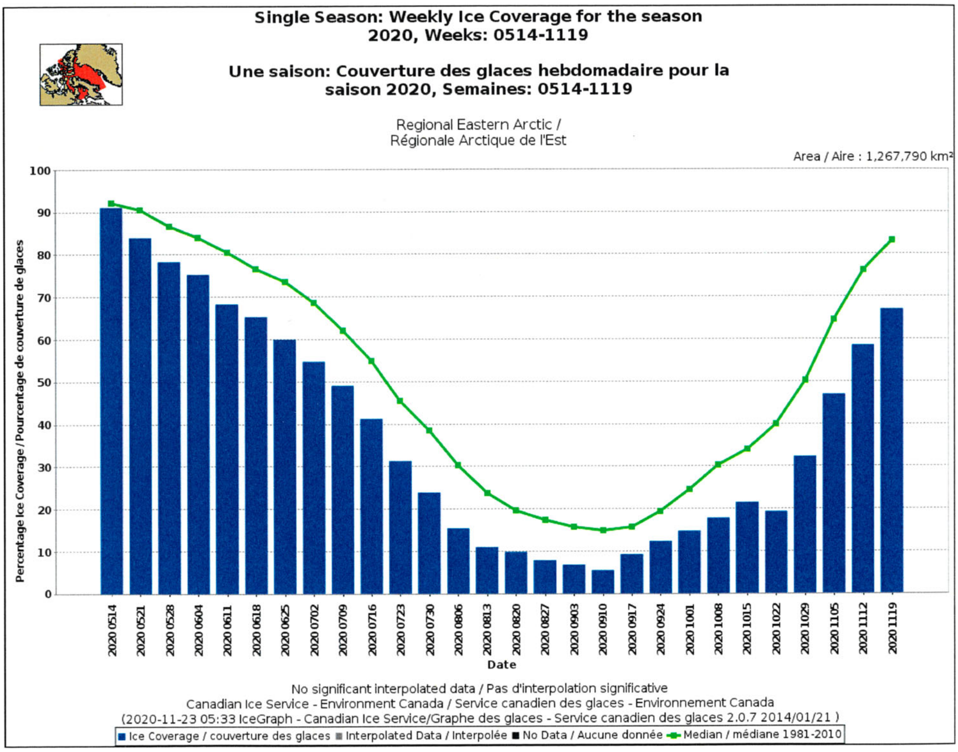

**Figure 5.** Weekly average ice cover in 2020 compared to the median from 1981 to 2010.

To support shipping in this dynamic environment, Canada has six heavy or medium icebreakers and nine Medium Endurance Multi-Tasked Vessels (MEMTV) with ice breaking capabilities. The majority of these (14 out of 15 ships) are available in the high Arctic, including Baffin Bay (Canadian Coast Guard, 2021). Denmark and Greenland have no icebreakers and rely on other nations for support, or the ice class 1A super-acquired Royal Arctic Line. As ice cover is usually thicker along the Canadian straits, it will require more resources to offer a reliable service to the increasing number of extractive companies, community supply vessels and transiting ships. For example, in 2018, impassable sea ice in Nunavut waters, coupled with too few Coast Guard ships, led to SC delays of up to three weeks. As stated by one of the operators, '[t]he Coast Guard does not have the assets to properly support the level of service that we agreed upon between Coast Guard and industry a long time ago' (Neary, 2018a).

### *Managing protective barriers*

Even under normal circumstances, supply vessels rely on support from government agencies. In Nunavut, Canada, supply ships work closely with the Coast Guard, which manages three medium-size icebreaker ships, to ensure SC reliability. In periods with extended sea ice or if the Coast Guard's resources become stretched because of operations in the south, the unreliable service means that ships cannot make it to harbour and continue to another community to deliver cargo, causing delays of weeks or months (Neary, 2018b; Rogers, 2016). While it is possible to complete deliveries to these communities later, the SCs rely heavily on improvisation (Downing, 2020). The resources available for the SCs of community supply vessels do not meet the current demand and are unreliable, despite technological developments. Even in Canada, where icebreaker capacity is available, there is a need for even more resources to meet the demand of ensuring SC reliability, as more bergy water is expected in the coming years (Clear Seas, 2020) due to increased calving from glaciers. In Greenland, the lack of icebreaker capacity makes SCs even more vulnerable, as seen in the Royal Arctic Line example in Ittoqqortoormiit (Scorsbysund). The lack of reliability is also evident in the company's approach to ensuring supplies to communities along the Greenlandic coast, where the target for timely arrivals is 80% (Royal Arctic Line, 2019). Supplying communities in the Arctic is challenging and expensive, requiring availability and effective coordination, with up-to-date sea ice data being essential to support decision-making and scheduling.

The SC also requires improvements to emergency infrastructure in order to cope with spills or SAR events (Dalaklis et al., 2018). For example, most helicopter SAR capacity in the Canadian Northwest Passage consists of forward operating locations that are not necessarily staffed and might not manage a significant incident (Royal Canadian Air Force, 2020). The Canadians have the majority of the SAR resources located further south in regions where there are more fishing and commercial activities, such as Goose Bay, Gander and Torbay, which, in practice, are out of reach for ships transiting the Northwest Passage. Greenland has two SAR helicopters (soon to be three), covering 2 million km$^2$, located on the west coast of the country where most of the population resides (Forsvarsministeriet, 2016). With an increase of 25% in traffic since 2013 and access to the Northwest Passage due to the retracting sea ice, the availability of SAR resources in Baffin Bay is an increasing concern. The Polar Code stipulates that the maximum expected time of rescue shall not be more than five days (International Maritime Organization, 2017). It has proved challenging to adhere to this goal during tests, indicating significant gaps in its practical functionality (Gudmestad & Solberg, 2019). Combined with the rudimentary SAR coverage in the high north, the effectiveness of this protective barrier is debated. While improvements are being made, there continue to be significant challenges to SAR infrastructure.

## Conclusion and discussion

A precondition for the Arctic region's industrialisation is the development of reliable SCs, both for ships transiting and vessels whose final destinations are Arctic communities. There is a wide range of Arctic hazards that SC planners must consider when managing their networks. While some significant technical improvements have been made, which enhance reliability performance, there will continue to be substantial delays. This paper has explored the hazards that face Arctic supply chain reliability in the region surrounding Baffin Bay and Greenland, as well as the technological and organisational developments that are adopted to mitigate these. The review included technical, operational, safety, environmental and reputational hazards that affect risk management decisions and drive innovation within SCs.

Using cases from the east coast of Canada, Baffin Bay and Greenland, we explored the challenges faced by three industries (community supply vessels, container traffic and bulk carriers) that regularly operate SCs in the region. We utilised a bow-tie approach to identify preventive and protective barriers implemented to ensure the mitigation of Arctic hazards, as well as to identify existing gaps that need to be addressed. Findings show that innovations in ship design have made significant advances which have improved the reliability of individual vessels, such as improved ice class designs and propulsion systems. While these design improvements have made transport possible, they do not entirely mitigate the challenges to SC reliability, as the examples of changes in ice coverage in the north-east of Greenland and increases in bergy waters in Canada show. These technologies are also not readily available, as they are expensive, and investments are not currently justified from an economic perspective. A driver which can potentially generate the introduction of necessary innovation is the increase in mining projects in the high north. The industry already drives a need for improvements to infrastructure, as the Bluejay Mining project shows, but more projects are needed to attract resources to the region. Another challenge to SC reliability is that icebreaker and SAR capacity is mainly available in the southern parts of both Canada and Greenland. With the increase in access and traffic, there will be a need for improvements in icebreaker and SAR capacity, if the SCs are to become reliable in the Baffin Bay area and Greenland.

Shipping companies have increasingly strong incentives to improve both preventive and protective barriers to increase reliability. The short shipping window in which the companies operate is a motivating factor which could engender investments in better technology. Both Greenland and Canada have an interest in industrial development, which would benefit both economies. Investing in infrastructure such as deep-water port facilities and SAR preparedness would send a signal to these companies that there is a willingness to support a potentially lucrative revenue stream. The establishment of these preventive barriers will provide an incentive for companies that rely on reliable SCs to establish themselves in the region. While the extractive industry creates local solutions for the shipment of products, the potential for nearby settlements and towns is far greater, as they serve as SC hubs for a region.

We must wait for the economies of scale, as protective barriers described in the Polar Code are, despite its flaws, instruments that increases ship safety and mitigate the impact on the people and the environment in the remote, vulnerable and potentially harsh polar waters. The code is a good starting point for improvements to both preventive and protective barriers, but it will need both more empirical testing and revisions if increased SC reliability in the region is to be achieved.

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