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# Identifying challenges facing reliable supply chains and ways to mitigate them for mining in the Baffin Bay region

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**Abstract.** There are substantial economic opportunities in extracting minerals in the Arctic region. However, it has proven difficult for operators to ensure reliable supply chains (SCs) north of the Arctic Circle. This paper uses a case study approach to illustrate the challenges of SCs reliability for mining projects in the northern Baffin Bay and on Greenland, discussing the technological and organisational developments that can mitigate them. A bow-tie approach shows the challenges faced by the industry and the effect of mitigating initiatives. We conclude that increased traffic will require technological, organisational and infrastructure developments to manage SC hazards and increase SC reliability. The available protective and preventive barriers have focused on avoiding periods where hazards could impact SC reliability. However, this strategy is unsustainable in the long term as a viable strategy for mining operations. It exposes the operations to Arctic hazards that are difficult to mitigate when time is limited. The consequence is that SCs often lack access to effective Arctic hazard barriers, ensuring increased SC reliability.

## 1. Introduction

Climate change resulting in ice melting has made an increasing area of the Arctic available for industrial development. Numerous mining companies have exploited these opportunities and are creating projects to extract major remaining untapped mineral resources globally. While these resources on paper look very lucrative, it has proven difficult for companies to turn a profit in many cases. Many Arctic risks have proven challenging to mitigate, and adaption is costly for companies, which have squeezed profit margins. One of the significant challenges has been and continues to be reliable SCs, both in providing essential ingredients, personal and equipment to some of these remote sites and getting the finished products to market. Shifting sea ice, changes in weather, ice melting, icebergs and issues related to permafrost are just some of the hazards these companies meet when managing their projects.

In July of 2021, the Baffinland Iron Mines Corp. announced that it would delay ice-breaking at the start of this 'year's shipping season to help protect the health of the summer narwhal population in Eclipse Sound [1,2]. The company operates the Mary River mine on northern Baffin Island, where it produces and ships up to six million metric tonnes of iron ore a year from nearby Milne Port.

In a news release, the mining company said it "will avoid ice-breaking activities" to help protect the narwhal in the area and only proceed with shipping once the ice around the port and entrance to Eclipse Sound is open [1]. The decision was based on direct response to Inuit input and recognising an important



community-based project that overlaps with the planned start of the Baffinland shipping season. The President and CEO, Brian Penny of Baffinland, stated that the company understands the importance of the narwhal, and also the importance of the construction of the Small Craft Harbour in Pond Inlet continuing this year, without knowing what mitigation measures might be placed on the Small Craft Harbour construction activity; "our decision to halt ice-breaking for the spring is based on the precautionary principle that is the foundation of our adaptive management plan". [2]

The example highlights both technical and social complexity that mining companies face when operating in the region. Challenging sea ice conditions, requiring support from one of the relatively few ice-breakers serving in the area, and the need to make the best use of a short shipping season drive companies to make investments in ensuring SC reliability. In addition, there are concerns related to the protection of communities and vulnerable local wildlife, which also impact the decision making that has direct consequences on the business. Mining companies around the world also face SC risks that affect reliability. However, very few are impacted by risks on the magnitude of the ones operating in the Arctic.

Mining operations are a complicated endeavour involving command, control, and coordination structures internally and between different points in the SC [3]. The combination of long distances, lack of infrastructure, limited navigational information, and frequent harsh weather events, make operations a challenging task at best. Numerous threats influence commercial development in the region as coordination is complex, including a lack of communication infrastructure, uncertain bathymetric data, and local sea-ice conditions can change within hours or days. SC management has traditionally focused on creating systems and implementing technology to ensure timely and reliable transfer of ingredients and finished products from one location to another. With climate change making the Arctic more accessible and increasingly commercially attractive, ensuring reliability and planning logistics are becoming increasingly challenging. With these factors in mind, we seek to answer the research question: What SC risks are mining companies facing in the region surrounding the Baffin Bay and Greenland, and what are the technological and organisational developments that companies could adopt 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 on risks and challenges related to SCs reliability in the Arctic. That section is followed by a description of the methodology, using arctic maritime activities to illustrate the hazards faced by commercial activities in the region, followed by a description of three SC activities faced by three case examples of mining companies operating or planning to operate in the area. We investigate the challenges the companies have identified to ensure reliability. The analysis explores how the Arctic threats impact the SCs and how the three companies accept, mitigate or prevent hazards having consequences for reliability. The last section answers the research question and debates the findings regarding increased accessibility to the region.

## **2. Theory – Current knowledge and state of the art**

The Baffin Bay region has witnessed increased traffic in recent years, which has made the need for research-based knowledge more salient. The following section identifies current knowledge and a state-of-the-art theoretical review on SC management of risks, specifically in the Arctic.

### *2.1 Identifying challenges in SC*

SC management is the coordination of information, resources, products and finances between interdependent organisations, defined as the management of upstream and downstream relationships between suppliers and customers to deliver superior customer value at less cost to the SC as a whole [4,5]. It has less to do with the needs of the 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 on SC in the Arctic provides a vantage point for understanding the complexity companies face when ensuring a reliable movement of goods and information.

The management of SC risks has traditionally been concerned with managing context-specific hazards and aims to ensure the integrity of the network as a whole [5,6]. It identifies and assesses the likelihood that hazards will occur and involves at least four steps: risk identification, risk analysis, risk evaluation and risk management, the last part of which can be broken down further into management, implementation and planning [7,8]. Using this structure becomes an enormous task when the 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" [9]. In a globalised world with interconnected SC networks spanning the globe, vulnerabilities can remain unseen to individual decision-makers, which makes it challenging to identify and manage risks [5]. 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.

Risks in the SCs centre around the disruption of "flows" between organisations [5]. These flows relate to 1. information, 2. resources, 3. products and 4. 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 supply chain. Finally, the flow of finances is, in this context, 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 resilience level.

When analysing SC risks, we look for events that affect the flow of information, resources, products, or finances [5]. To protect and prevent events from impacting these flows, organisations are implementing preventive barriers, which are organisational or technological, that will prevent or mitigate a hazard from turning into a risk event. If an event should materialise, the organisations have protective barriers to prevent or minimise unwanted consequences [10]. The bow-tie model in Figure 1 below describes, on the left side, how preventive barriers are created to ensure that events do not materialise and, on the right side, how – if an event should occur, how the organisation can create protective barriers to mitigate or prevent events from having negative consequences.

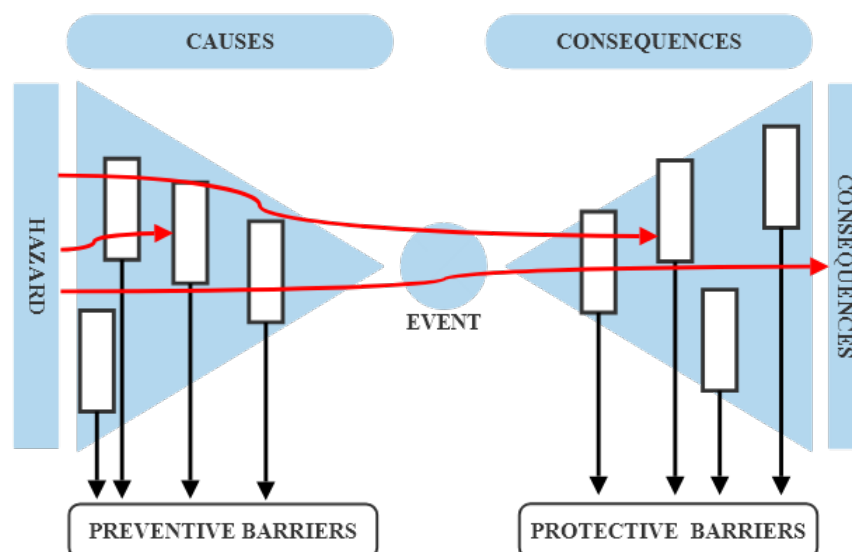


Figure 1. Bow-tie model

## 2.2 Identifying risks in Arctic SC

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 and particular and unique hazards. As described above are changes to the information, resources, products, and financial flows at the centre of SC risk analysis. Table 1 below illustrates Arctic hazards that can affect the reliability of an SC network [11–17]. The hazards are categorised into four themes: technical, health and safety, environmental and reputation. Technological hazards are changes in the environment that impact the 'ship's ability to manoeuvre and maintain structural integrity under Arctic conditions. Health and safety hazards have to do with the 'crew's health and safety and the coordination of an effective response. Environmental hazards concern the impact of a catastrophic event on the fragile Arctic environment and the mustering of an adequate response. Reputational hazards focus on how organisations maintain legitimacy with stakeholders and their legal and social licence to operate.

**Table 1.** Arctic hazards that can affect the reliability of an SC network [11-17]

Technical hazards	Health and safety hazards	Environmental hazards	Reputation hazards
Polar lows, strong winds, heavy snowfall	Fire	Hazardous materials/chemical spill	Breach of legislation and standards set by authorities
Darkness	Severe weather	Long-term environmental impact of small spills	Effect of pollution on the maritime environment
Uncertain meta ocean data	Lack of IT and phone communication	The remoteness or lack of emergency response	Lack of accurate information about the local context
Sea ice and icebergs	Health and safety at work (work environment)	Inadequate or insufficient community response	
Marine and Atmospheric icing	Lack of qualifications and competencies		
Power loss due to mechanical failure	Communication and language barriers		
Loss/contamination of water supply	Health emergencies		
Uncertain or lack of bathymetric information	Avalanche/Tsunami		
Reduced satellite coverage	Airborne diseases		
Remoteness and lack of infrastructure, emergency response, logistics			

## 2.3 Identifying existing measures to prevent Arctic SC hazards

Different forms of technology have been applied to the Arctic SCs to ensure access and reliability of these new technologies come in the form of land-, sea- and space-based innovations, from improvements of port facilities to the development of ice-breaking capabilities that free up resources from individual ships and place some responsibility on the countries with the jurisdiction [18–20]. However, there continue to be significant gaps in the development of infrastructure in the Arctic. These gaps will ensure that individual shipping companies and nodes endure extra costs when transiting or servicing their

production sites. For example, significant parts of northern Greenland and Canadian communities are without port facilities, and goods need to be brought in by barges [21].

When it comes to managing safety hazards, the eight Arctic countries – Canada, the United States of America, Russia, Denmark, Norway, Sweden, Finland and Iceland – have signed agreements supporting and helping coordinate emergency response to create more resilient SCs and protect the fragile Arctic environment [22,23]. The agreements state that the Arctic countries shall assist persons, vessels, or other crafts 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 complicated 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 several thousand persons (passengers and crew). Still, other industries are also at risk, as the shipping industry is transporting oil, gas and mineral ore through the region. The general increase in traffic by the shipping industries has arrived with the retracting sea ice and more extended open water periods. Figure 2 shows the ships that sailed in the high Arctic (white lines), including the Baffin Bay and the coast of Greenland in 2020 [24].



**Figure 2.** Shipping routes 2020 Baffin Bay region

Environmental hazards are a concern not only for the Arctic communities themselves but for a wide range of stakeholders outside the Arctic. Special interest groups work to remove or reduce the impact of industrial development in the area, working with local and international stakeholders. Hence, several treaties and agreements have been signed to prevent adverse environmental changes impacting the region [25–27]. While enforcement of these treaties has proven difficult, they represent a significant steppingstone for ensuring that environmental impacts are being addressed locally and in an international forum, the International Maritime Organization, IMO.

Reputational risks have been one of the most challenging hazards for mining companies to manage [28]. Companies in the region have been faced with managing the complex technical, safety and environmental risks linked to operating in the area, and even smaller projects attract the attention of a wide range of influential stakeholders. Even mines close to starting construction have faced stakeholders who have impacted the project in very tangible ways. For example, a rare earth element and uranium project close to getting the final permits for production in southern Greenland was the focal point of a political election [29]. A highly critical party won the election, resulting in the postponement and possible termination of the project at the cost of several hundreds of millions of dollars.

While we have significant insights into SC management and the hazards faced by companies transporting goods, we know less about how to manage the context-specific Arctic risks. We propose that this gap can be addressed by using a bow-tie approach. While the tool is mainly used within safety management, we believe it can be utilised as a practical instrument for companies wanting to manage preventive and protective barriers, thereby strengthening the robustness of their SC. Working systematically with both causes that lead to events and the consequences that these are included within a single framework supports the ability to get products to market.

### 3. Methodology

Using three cases of mining companies experiencing SC risks from Greenland and Canada, the aim is to show how the bow-tie approach provides insights into the technological and organisational innovations that operators can utilise to improve reliability. We use the methodology to illustrate how SC operators experience challenges that affect reliability and the actions that they have taken to overcome these. The analysis focuses on the movement of physical goods to and from the mine sites.

The three cases consist of two mining projects in Greenland and one from the east coast of Nunavut in Canada. The project is a case located at around 83 degrees North at the very top of Greenland. The project, which is still in the planning phases, has one of the 'world's largest Zinc and Lead deposits and is managed by Ironbark mining [30]. The second project is located on the west coast of Greenland and is one of the two existing production projects in the Arctic. While this Canadian owned Hudson mining operation is relatively small, it produces and ships products to markets in the US [31]. The third project, the Mary river mine, has been in operation since 2014 and is believed to hold one of the largest iron ore deposits in the world. Baffinland Iron Mines Corp manages the site, which has expanded the project considerably [32].

Preventive barriers are analysed, using empirical examples related to the development and introduction of technology that the industry has adopted. Of specific interest is introducing technology that improves reliability and could mitigate technical, safety, environmental and reputational hazards. We identify two types of preventive measures, namely, the ones associated with the transport of information, resources and products from one point to another within the SC and the other related to the physical infrastructure necessary for mining operations. We have looked for technologies that explicitly mitigate the identified Arctic hazards (see Table 1) and incorporate them into ship designs and infrastructure development.

An effective response to hazard events in the seas surrounding Greenland and north-eastern Canada is essential for robust protective barriers. We also investigated the availability of ice-breakers 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 [33] and helping vessels that cannot break free from sea ice independently. The 'region's search and rescue (SAR) capability provide 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 [34], leading to updates of the IMO Polar Code [25].

The following analysis explores how different SCs have dealt with risks in introducing technologies as preventive barriers and protective barriers that can mitigate the consequences if an unwanted event materialises.

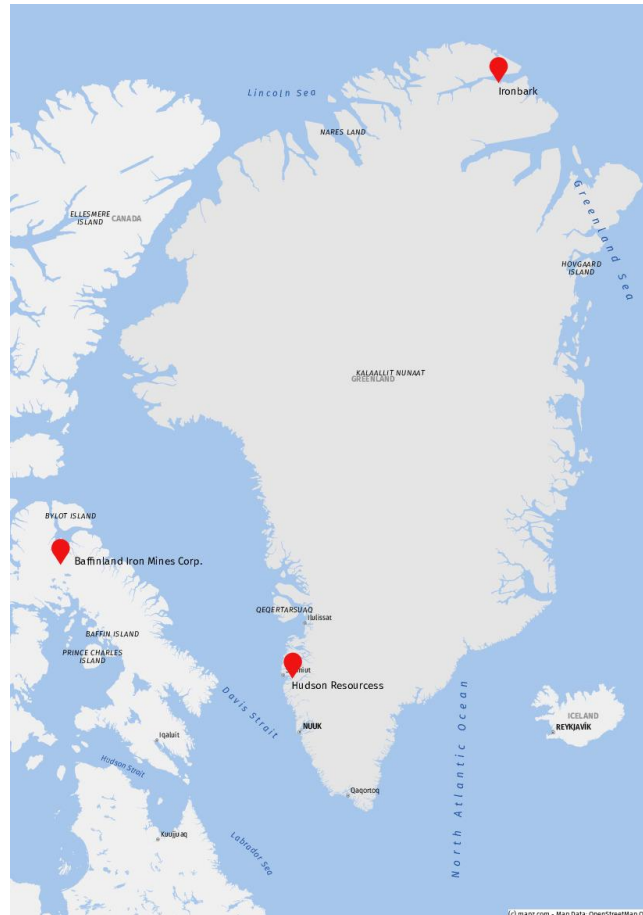


Figure 3. Location of the three case study sites (authors own design)

#### 4. Analysis

In the following section, we analyse, using a bow-tie approach, the three cases as to SC threats and the risk management activities the individual organisation has implemented or are planning to ensure reliability. The analysis of cases are structured using the bow tie as a framework focusing on preventive and protective barriers. Figure 3 depicts the location of each of the three case sites.

##### 4.1 Ironbark mining

The Ironbark project in Citronen Fjord is the most northern project at 83 degrees North. Nyrstar and Glencore, two of the major world producers of zinc, finance the Australian company. In late 2016, Ironbark was granted a 30-year mining licence by the Greenland government, and in September 2017, Ironbark released a cost update to its 2013 feasibility study [35,36]. The estimation is that the sale of zinc and lead will produce a lifetime revenue of 6.364 million USD, using 2017 prices. Exploration costs are estimated to be 50 million USD [37]. The mining project initially includes two underground mines that, at a later stage, will be developed into an open pit.

The mine is expected to be operational for 13 years. The closing process will take another three years. However, there are possibilities that operations will be extended as more geological knowledge is



collected when production starts [30]. Ironbark estimates that some 300 employees will be required during the construction phase and 470 as soon as the organisation enters production.

According to the company, the Citronen Fjord deposits represent one of the 'world's largest undeveloped zinc deposits, with 5.8 billion tons of zinc. Mining will take place all year round with a three-month shipping window due to sea ice conditions. However, the relatively short shipping period has made investors hesitant to further develop and invest in the project [38–40]. The potential lack of access is the leading risk that the project faces. Despite attempts to prove that it is possible to access the site, the efforts have proved unsuccessful. In September of 2018, Ironbark tried to sail a cargo ship into Citronen Fjord but could not complete the last part of the journey due to sea ice build-up [41,42].

The bow-tie approach illustrates how Ironbark mining is working with strengthening preventive and protective barriers. It is yet to be made feasible to traverse the north-eastern coast of Greenland with bulk carriers and the harbour infrastructure needed to be put in place at the mine. Both issues have proven difficult to manage as investors have been doubtful about the feasibility of Ironbark's plans [42]. The unsuccessful journey being one such example. Four specific events impact the timing of the relatively short shipping window at Citronen Fjord.

- Ice fracture in the Frederick Hyde and Citronen Fjords – the annual separation of the sea ice from the land, often occurs in July, which constitutes the earliest shipping time.
- Seasonal melt in the adjacent Wandel and Greenland Seas – the annual partial melt of the sea ice offshore, made up of seasonal (first year) and perennial (multi-year) ice.
- Openings in the sea ice pack are impacted by local weather conditions, which allows for the traverse of the shipping route with little to no interaction with areas of high ice concentration but could also mean that lanes are closed with short notice.
- The autumnal freeze up and ice cover expansion and the formation of new ice are subject to local weather conditions in the early stages. These technical challenges relate to causes in the bow-tie, which could evolve into an event where the cargo ship would be either stuck or suffers damages due to ice. Figure 4 depicts an example of changing ice conditions at Citronen Fjord.



**Figure 4.** Example of Fast Ice Fracture at Citronen [30]

*Applying the Bow-tie approach using protective and preventive barriers:* Remoteness and lack of infrastructure are concerns that need mitigation or adaptive preventive barriers. Ironbark has taken steps to manage the threat of sea ice to its SC by establishing protective barriers. The company is planning to create living quarters, emergency management, a powerplant, storage facilities, a harbour, and a small airport, which will make the mine independent from outside help. These measures include protective production at the site in case that the site cannot be resupplied by ship, as well as living quarters and

other essential services. Ironbark cannot ensure reliability in its SC if it continues to be unable to introduce practical preventive barriers in the form of cargo ships with sufficient ice-class capabilities.

Improvements in ice-class ships have made it more feasible than commercial shipping can be carried out in ice-filled waters. However, these types of vessels are expensive and might not be available on short notice, making them an unreliable preventive barrier. Investments in infrastructure that would place the port close to the inlet are possible, but would present its own logistical and economic challenges as building and maintaining roads in the area is at best challenging. Hence, there is currently little in the form of preventive and protective barriers that would help Ironbark ensure free passage of goods to and from the mine. It should, however, be noted that the double-hull tanker design could be used for the ships carrying the ore. This design is being used by the ships carrying LNG from the Ob Bay LNG facilities to the Far East through the Northern Shipping Route and by tankers transporting ore in the Arctic [43]. Furthermore, the experience from Russian arctic harbours, like the Sabetta harbour when LNG is shipped out, should be relevant. Such investments will be expensive and less feasible at a stage in the project where it still needs proof of concept.

#### *4.2 Hudson resources*

Hudson Resources is a Canadian based mining and technology company focused on developing the unique White Mountain (Qaqortorsuaq) anorthosite (calcium feldspar) mine in Sønderstrømfjord [37,44,45], See Figure 5. The company refines Anocrete, which potentially brings significant environmental benefits and cost savings to the construction industry. The final product has applications in the fibreglass, alumina, filler, paint and white cement markets. The mine has a 50-year permit and an expected mine life of 120 years. The mine came into production in the first half of 2019 and has a 10-year supply agreement with one of the world leaders in fibreglass production.

Twenty persons were involved in the construction phase; most were non-Greenlandic, mainly due to a local labour shortage [44,46]. Approximately 57 full-time positions in two shifts are required when the mine is fully operational. The anticipation is that the 'mine's work season will run for eight months due to potential ice conditions, while the processing plant will run ten months per year. Production halted for two months in the spring of 2021 due to a lack of labour, which could heavily impact the targets set for the year.

#### *4.3 Applying the Bow-tie approach using protective and preventive barriers*

The bow-tie approach shows how Hudson is working to reduce the impact of operating in a region with periods of sea ice and icebergs by applying preventive barriers. The decision to ship for eight months a year is meant to ensure that the SC avoid periods where there is sea ice and blockages due to icebergs in the area. While this reduces production and market access, it increases reliability and makes planning schedules more robust. As customers in the North American construction industry rely on a steady and reliable supply of ore, the conservative approach to SC reliability seems to be meeting their expectations. By working with preventive barriers in the form of a conservative approach to the delivery of products, Hudson can improve its ability to meet customer expectations. Hudson has done little in the form of protective barriers and is therefore vulnerable to other forms of threats. As the case suggests, lack of access to qualified employees might have been overlooked and have impacted production time at the mine. These types of events make this approach uncertain as to the possible prevention of an SC risk event. While the site is reachable by boat (4-5 hours) or helicopter from the nearby town of Sisimiut, it is difficult to get enough labour to work at the site for more extended periods. Hence, there is a risk that local issues like lack of access to qualified works will directly impact production and, thereby, the SC. Protective barriers could be introduced, for example, by employing more foreign workers to fill the production capacity gap.





**Figure 6.** Mary River project and location [47].

## 5. Discussion and concluding remarks – Applying the bow-tie approach to SC reliability

The Bow-tie approach focuses on identifying hazards that can evolve into events, which can impact an organisation and the consequences such an event can have. To mitigate or prevent hazards and consequences are companies applying preventive and protective barriers. Some of these can be multilayers incorporating several measures, as seen in the Baffinland Iron Mines Corporation example where both preventive and protective barriers are applied. While in others, such as Hudson and Ironbark, there are fewer barriers, making them vulnerable to SC risks in other areas, such as access to labour or inadequate ice-breaker capacity. The Baffinland Iron Mines Corporation is experiencing a change in hazards due to climate change (increase in bergy water), which presents the company with new challenges related to constructing an alternative port. In all cases, there is a need for preventive and protective barriers to be strengthened to counter the changes in hazards that the companies are experiencing. The bow-tie approach provides a structure that mining companies can strengthen their SC and become more robust towards Arctic hazards. Using a system of preventive and protective barriers enables better utilisation of resources and the opportunity to create structures that will mitigate or prevent more than one hazard at a time. The consequence is that organisations use fewer resources to protect their SC and become more robust towards disruptions.

Greenland and the area surrounding the Baffin Bay are considered lucrative for mining companies to explore the many undeveloped mineral deposits in the region. The region has seen a surge in projects spurred by increases in mineral prices and prospects of large unexploited deposits. One of the significant obstacles to the establishment of a viable mining sector is, however, ensuring SC reliability. The use of redundancy strategies seems to be the preferred approach to SC reliability for the three mining projects.

The Baffinland project is constructing a new port and has used ice-breakers, which provide a more robust operation to ensure a continuous supply of products. For the Hudson resources mining operation, this option is not available. Here, the plan is to reduce the production and shipping window to accommodate seasonal ice coverage. Both of these options seem a less likely strategy for Ironbark as alternative ports at the coast would be expensive at this stage of the project, and even more, conservative use of the shipping window, which is already only three months, is unfeasible. Operating SC in the

Arctic is an expensive endeavour. While technical and organisational solutions to these challenges exist, they are often associated with significant expenses, either in infrastructure construction or reduced production windows.

Organisations using time, in the form of a reduced shipping window, as a resource is a strategy that will directly impact the profitability of both Ironbark and Hudson, creating more risks that the company needs to address. Hudson has already experienced this vulnerability as it lost production time, making its SC even more vulnerable. While reducing production and shipping windows might be a viable strategy in the short term, it will weaken both preventive and protective barriers to SC reliability. Hence, well efforts to introduce new measures be less effective as events like temporary lack of access to labour have a proportional more significant consequence.

Climate change is a factor, which already or shortly will impact all three projects. Changes in sea-ice patterns in the Baffin Bay have made the northern part of the region more accessible and meant more bergy waters. These changes will lead to less use of ice-breakers but will mean that bulk carriers needs to be of a higher ice-class as they will encounter an increased number of ice flows and bergs. The Ironbark project is planning for less ice and hence an extended shipping period. These predictions can be impacted by changing consistency to ice from continuous ice-flows to waters with bergs, flows and blue ice (ice beneath water which is hard to detect). Also, changes in permafrost will impact any infrastructure that the companies build, including the ports, which needs to withstand higher variations in precipitation and temperature. The increase in climate-related costs will significantly challenge the feasibility of some of these projects and is as yet an unknown factor in project cost estimation. Climate change is something new that mining companies will have to find practical barriers to confront. While it is unlikely that these changes will introduce entirely new hazards, the expectation is that known events will have different consequences, like less ice means more bergy water as already described.

For companies like Ironbark, it has been challenging to provide proof of concept feasibility to potential investors, especially for mining companies in Greenland. There are fewer available resources from the Greenlandic state, and the infrastructure is rudimentary at best, which means companies themselves will have to establish most of their needs. In practice, this translates into increased construction costs. Also, with the addition of context-specific Arctic risks can these costs be underestimated, leading to budget overruns. The company believes that climate change will help the company proving that SC reliability is feasible but, in the process, neglect that these changes can increase hazards making existing barriers less effective.

Using the bow-tie approach makes it possible to structure the organisation's preventive and protective barriers within a unifying framework. SC risks are diverse and involve both internal processes as well as impacts of external forces. Using the bow-tie looks at both causes and consequences as elements of the same system, thereby making the organisational response more efficient and possibly more effective if the barriers meet the specific challenges faced. However, the tool also requires a more dynamic approach to risk analysis, which includes long-term changes to the context in which it is applied. The example of climate change effect on SC reliability is such a change that will directly impact both preventive and protective barriers.

We aimed to answer the research question of what SC risks mining companies face in the Baffin Bay and Greenland region and what are the technological and organisational developments that companies adopt to mitigate these? We used three cases to show how risks impact SC decision-making, representing different challenges and mitigating barriers. While all mining companies have adopted technical and organisational solutions to reduce risks, it has been challenging to secure SC reliability. Ironbark continues to struggle with plans to ensure ice-free sea lanes even within a relatively short shipping window. Hudson has shortened shipping periods to ensure a greater probability of ice-free waters, but encounters labour shortages. Baffinland is planning a new harbour further south where there is a greater chance of year-long shipping but struggles with meeting community expectations. One major factor has been the maturity of the individual projects as Ironbark needs to establish a viable proof of feasibility, which will convince potential investors. Both Hudson, which started operations in 2018 and Baffinland

that started in 2014, has already established mining operations, while Ironbark still has to prove their concept.

Time has been used to reduce consequences in SC reliability but has also weakened other barriers. A reduced shipping window is a short-term solution to complex problems that these companies are facing. While the solution can be seen as attractive, it has provided companies like Hudson with new challenges and very little room to manoeuvre, providing alternative operational solutions. Hence, the use of time as a barrier to hazards only present these organisations with new challenges.

It is difficult to anticipate the full effects of climate change on SC reliability as we have yet to know the extent of local impacts. It is possible to take mitigating steps with current knowledge and insights into how we anticipate evolving Arctic hazards will evolve in the coming years. Firstly, use of recent improvements to ships design and ice-class ships as seen implemented in other parts of the Arctic. New technology will improve reliability to making preventive barriers more robust and thereby the ability of companies to bring their products to market. Secondly, further development of the Polar Code can improve management planning and thereby positively impact reliability. While the Polar Code main concern is safety at sea, it can also be a tool for companies to manage the Arctic specific risks that can influence SCs, targeting preventive barriers specifically. Thirdly, better tools for predicting sea-ice movement and areas of bergy water will help plan the movement of products from the mine to customers or production sites. Prediction of sea-ice movements is a difficult task as many local factors can impact the forecast. However, with recent innovations in satellite technology, maritime maps and metrological information, it is possible to reduce uncertainty in the risk assessments and improve SC reliability.

SC reliability in the Arctic requires significant investments often associated with redundancy strategies as witnessed in Baffinland or by taking conservative risk assessments as done by Hudson and Ironbark. Both approaches are costly as they will either require infrastructure investments or reduce the potential maximum production output. The use of time as a strategy for hazard mitigation seems not to be a viable option as Hudson encountered additional events impacting SC reliability in the form of reduced production time due to lack of labour. Implementing new technology or getting access to innovations will increase these costs further, making improving SC reliability even more expensive. However, as these technologies become more widely available, the investments needed will decrease in the coming years, making SC reliability a more achievable goal.

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