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Cognitive Task Analysis to Understand Icebreaker Decision Making

M. Musharraf[1], K. Kulkarni[1] & S. Mallam[2,3]
[1] *Marine and Arctic Technology, Aalto, Aalto University*
[2] *Memorial University of Newfoundland, St. John's, Canada*
[3] *University of South-Eastern Norway, Borre, Norway*

ABSTRACT: Icebreakers are a critical shared resource between Finland and Sweden required to keep the Baltic Sea clear for differing waterborne activities throughout the winter season. The safety and efficiency (both ecological and in terms of time) of the winter transport system is highly dependent on the decision-making process followed by the icebreakers. The captains in charge of the icebreakers must decide the priority of assistance among all the merchant vessels that may be in need within a given time window. While captains successfully do this every year, with experience, this decision-making becomes second nature and a transparent picture of how the decisions are made is often missing. It is not always clear what salient features captains pay attention to, and how they use those features in their reasoning process to reach a decision during operations. This paper presents a pilot study that uses cognitive task analysis (CTA) to outline captains' decision-making process for ice breaker assistance allocation. In-depth interviews of three subject matter experts were conducted using a naturalistic icebreaker scenario. Results include identified critical decision points, identified, and prioritized salient features, and characterized icebreaker assistance strategies.

1 INTRODUCTION

The Baltic Sea is an important socio-economic zone with countries in the Baltic Sea Region (BSR) depending on it for movement of traffic and goods all year round. The northern part of the Baltic Sea, the Bay of Bothnia, experiences strong winters resulting in ice-covered waters for nearly 5 months each year [1]. To ensure the safety and efficiency of traffic in winter in this region, icebreakers are often employed to assist vessels. The icebreakers are a critical and shared resource, often jointly managed by the traffic authorities of neighbouring countries (such as Finland and Sweden). The icebreakers perform many tasks during the months from October to May, when the sea is usually covered in ice. Icebreakers create and maintain channels in ice called directed pathways (dirways) which are then used by other vessels, that are not designed for icebreaking capabilities, to operate in. Icebreakers also tow vessels with lesser icebreaking capabilities through regions with tougher ice conditions. They help vessels navigate the tricky fast ice region closer to the ports [2]. Operating, maintaining, and coordinating icebreakers are expensive [3]. Hence, the icebreakers always try to optimize their trips, assisting multiple vessels at a time whenever possible and reducing their own travel time. It is often the case that the number of vessels requiring assistance at a given moment are more than the number of icebreakers in service. The icebreakers are then tasked with prioritizing the assistance requests. These priorities need to consider multiple factors such as average waiting time, fuel consumption, distance to be travelled, expected departure/arrival time of vessels from/to ports, and safety requirements. Icebreaker decision-making is thus a complex task, involving multiple dynamic factors and system-level Key Performance Indices (KPIs) [3]. These decisions are currently managed by the icebreaker captains with the support of other expert seafarers on land [4].

In the recent years, maritime traffic authorities are additionally faced with challenges emerging from climate change [1]. On the one hand, the winters are more unpredictable with more brash and slushy ice, and on the other hand, vessels are now required to be Energy Efficiency Design Index (EEDI) compliant for fuel efficiency, which results in lesser ice breaking capabilities. The policymakers are now interested to understand how these changes are set to affect the icebreaking needs in the coming future. This has resulted in multiple research efforts, especially in the BSR universities, to study and predict the future of icebreaking under climate change challenges [5][6]. While many of these works have been successful at capturing the ice dynamics, the traffic flows, and the vessel performances, the one aspect that has been hard to model is the icebreaker decision-making.

Previous attempts at capturing this decision-making process have resulted in logic-driven and/or mathematical algorithms [6]. However, when compared with historical data during validation studies, large gaps were identified in the actual data and the modelled versions. One reason for this gap is that the purely logic-driven approaches fail to count the human factors (such as the on-the-job adjustments made by experts to suit dynamic situations) that are involved in the decision making. This paper uses a cognitive task analysis (CTA) approach to elicit knowledge about icebreaker decision-making from the subject matter experts. This allows capturing the human element in the decision making.

A pilot study with three participants has been conducted. The participants were recruited based on their experience with the Finnish-Swedish winter navigation system. Among the available CTA methods, the Critical Decision Method (CDM) [7] has been used with a predesigned naturalistic ice-breaker scenario and predefined probes. While the results of the study are preliminary, they show that the CDM method can be useful in identifying critical decision points, identifying, and prioritizing salient features, and characterizing the strategies used. The outcome of this study is expected to increase the realism of winter navigation simulation tools that involve icebreakers, contribute to intelligent decision support systems for winter navigation, and generate training materials that will be useful for less experienced seafarers tasked with ice breaker decision making.

2 COGNITIVE TASK ANALYSIS AND THE CRITICAL DECISION METHOD

CTA is an approach implemented to uncover what people know and how they think, to better understand the mental processes that underlie observable behaviour [8]. CTA describes a collection of differing methods that are an extension of the traditional task analysis approach to describe knowledge, thought-processes, mental strategies, and goal structures of actors in complex systems [9]. Among the many CTA methods available, CDM is used in this paper. The CDM aims to achieve knowledge elicitation through cognitive probing and reflection as a form of retrospective CTA technique [10]. CDM is commonly used to elicit specialized knowledge from subject matter experts across a diverse number of domains to better understand expert decision making and reasoning in naturalistic settings [11]. Although CDM was primarily intended for non-routine events [10] CDM can also be applied to both routine and non-routine analysis of highly specialized or difficult events and tasks, especially when decision-making and actions of experts may differ from those with less experience [12].

CDM is implemented through a semi-structured interview approach, typically consisting of seven steps: i) define the task or scenario under analysis, ii) select CDM probes, iii) select appropriate participant, iv) gather and record account of the incident, v) construct incident timeline, vi) define scenario phases or decision points, vii) use CDM probes to query participant decision making. This study uses the typical CDM steps with some modifications. Steps iv and v which are purposefully designed to analyse non-routine retrospective incidents, were eliminated from the current study as the focus is on typical ice-breaking scenarios. The other steps also needed some small adjustments to fit the purpose of the study. The steps are described in the following subsections with more details.

2.1 *Define the task or scenario under analysis*

The first step focuses on defining the task or scenario under analysis. Unlike typical CDM applications where focus in on non-routine incidents, the current study focuses on a typical ice breaking scenario. However, ice breaking itself is a highly specialized task and even for typical scenarios the decision-making is quite complex in nature.

The scenario used in the study focuses on the Northern Baltic Sea, the Bay of Bothnia region. The scenario is a snapshot of a situation in winter, in line with some of the commonly occurring instances in winter navigation. During scenario development, academic collaborators with prior experience of working with seafarers were consulted for understanding what information are crucial to design a credible scenario. Figure 1 shows the scenario that was presented to the participants. Four vessels are shown to exist in the system (that is, the area under observation: Bay of Bothnia) at the time of observation. The vessels are assigned details such as ice class and name. Discussion with academic collaborators during the scenario design phase revealed these details as crucial. While other ship details (such as hull type and propulsion power) were also deemed important it was concluded that captains and seafarers who work in the region on a regular basis can infer the other vessel details from the vessel name. The vessel name and ice class were assigned from a set of vessels that frequently navigate this area using public data sources [13]. The locations and departure times of the vessels were inspired from instances that occurred during simulation runs of a winter navigation simulation tool [6] developed at Aalto University. The tool uses inputs from Automatic Identification System (AIS) data for the year 2018. Additional information that was

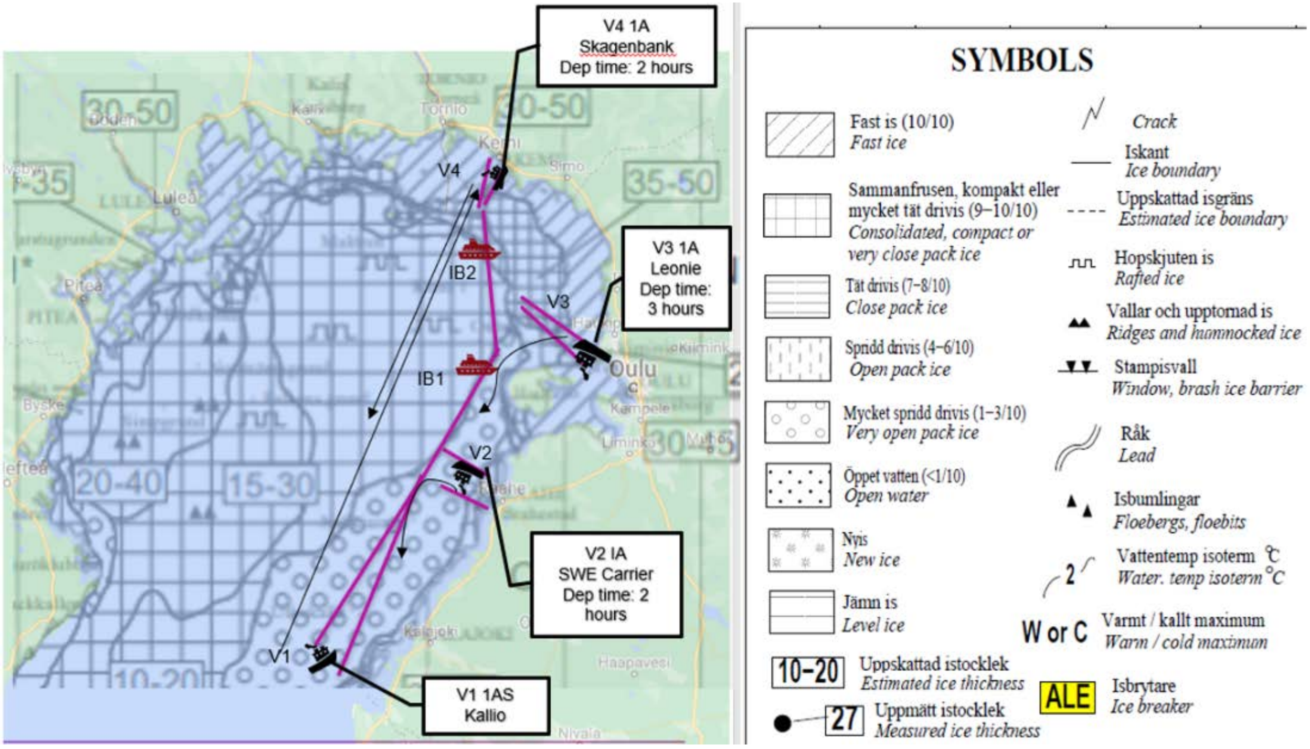

Figure 1. a) Scenario under analysis with 4 vessels and 2 icebreakers b) Symbols for ice information in (a).

identified as crucial was the prevailing ice condition. Historical ice data [14] from the Finnish Meteorological Institute (FMI) were used to represent the ice conditions. In practice and in the simulation, the icebreakers operate in their assigned zones, prioritizing the vessels in their zone. This information is not drawn explicitly in any chart and the zones are decided dynamically by icebreaker captains.

In Figure 1(a), V indicates vessel and IB indicates icebreaker. Both IBs have the same capacity to create a wide enough channel. The black directed arrows at the vessels' end indicate the direction of intended travel of the vessel. The pink lines indicate channels. Single line indicates closed channels. Two lines indicate open channel. Some channels are partially open (near V1), some are fully open (near V2). Narrowing width of channels indicates that the channel is progressively closed. Figure 1(b) shows the interpretation of the symbols used for ice information in 1(a).

Given the scenario, the participants were tasked to prioritize the vessels for assistance assuming they were in charge of the icebreakers. With assistance from the analysts, the participants described how they would use the icebreakers to help the vessel in need until all vessels are either safely at a destination port or are safely navigating.

2.2 *Select CDM probes*

Since the aim of the study was to identify and prioritize salient features and characterize the icebreaker assistance strategies, the CDM probes were designed accordingly. The set of probes relevant for this paper is presented in Table 1.

Table 1. CDM probes for investigating ice-breaker decision making

1. Goal specification	What were your specific goals at this decision point?
2. Cue Identification	What features were you looking for when you formulated your decision?
3. Information integration	What was the most important piece of information that you used to formulate the decision?
4. Situation assessment	Except for the information given to you, was there any additional information that you might have used to assist in the formulation of the decision?
5. Basis of choice	Do you think that you could develop a rule, based on your experience, which could assist another person to make the same decision successfully? Why/Why not?

2.3 *Select appropriate participant*

Since this is a pilot study, the participant pool was limited to 3. The participants were recruited based on their experience with the Finnish-Swedish winter navigation system. Inclusion criteria required that participants were certified nautical officers and had experience with ice navigation in the Baltic Sea. The participants had between 17-25 years' experience working at sea in various operational positions, with two of the participants also having additional management experience in planning and executing winter navigation. Define decision points and use of CDM probes to query participant decision making

The decision point identification was done in conjunction with the participants. It was agreed that every time the icebreaker is taking a new decision (e.g., deciding on a new vessel to assist, deciding to form a convoy) it can be called a new decision point. However, all participants agreed that their answers to probe questions would not change for the different decision points. Keeping this in mind, the probes presented in Table 1 were used once per participant per scenario rather than per decision point.

3 DATA ANALYSIS AND RESULTS

To increase the reliability of the interview process and data collection, two analysts were used throughout the CDM steps mentioned in section 2. Several data were collected but the data that has been analysed for the purpose of this paper includes notes from the analysts and notes (along with drawings) from the participants (if any were produced during the CDM interview process). While audio recordings were taken for each participant, they have only been used in this paper to resolve conflicts that arose while comparing notes of the two analysts, as a form quality assurance and inter-rater reliability. Two direct outcomes of the analysis were 1) the participants' answer to the question regarding prioritization of vessel as described in section 2.1 and 2) a CDM table with the participants' answers to the questions listed in Table 1. The CDM table can be further analysed to identify and prioritize salient features, and characterize the strategies used. One indirect outcome was an evaluation of the credibility of the scenario and suggestions on how the scenario can be further improved for a future full-scale study.

The following subsection summarizes the most significant outcomes of the study.

3.1 *Prioritizing vessels for assistance*

For the scenario presented in Figure 1, participants discussed how they would prioritize the vessels in need and plan assistance until all vessels are either safely in port or are safely navigating.

For the first assistance decision (decision point 1), some similarities across participants were observed. All participants agreed that IB2 should assist V4 first. Regarding IB1, two participants chose that IB1 should assist V3 first. Both participants mentioned that V1 and V2 can sail independently at least for a while given their ice class. The other participant used IB1 to assist V2 first. At the next decision point, again some similarities in decision making were observed across participants. Two participants mentioned that V3 and V4 may construct a convoy that can be assisted by IB2 until the zone crossing and then the convoy can be handed over to IB1. One of these participants mentioned that V2 can also join this convoy later. While V1 was identified to not need help, two participants mentioned that it can be assisted by IB1 if needed but only after the other assistance has been taken care of (so not a priority), and at the zone crossing IB2 can take over V1.

3.2 *Salient features and strategies used*

Questions 1 and 5 in Table 1 focused on the strategies of icebreaker assistance while Questions 2 to 4 focused more on identifying and prioritizing salient features.

When asked about goal specification (Question 1, Table 1), it was realized that traffic safety is of utmost importance and the goal is always to ensure this. Given that this is usually already considered in terms of ice class of the ships and assistance restriction, the goal in hand is to minimize the overall waiting time of the vessels. Next goal would be to optimize fuel consumption, and this goes hand in hand with optimizing overall waiting time of vessels. All participants had the same view on this question. The goals specified by the participants and their priorities are presented in Table 2.

Table 2. Goal specifications and priorities

Goal	Priority
Traffic safety	1
Minimize overall waiting time for vessels	2
Optimize fuel consumption	2

Regarding the features that are important for decision formulation (Question 2, Table 1), participants had slightly different views. All participants identified Expected Time of Departure (ETD) of the vessels as an important feature. Ice condition and ice class of vessels were identified as important features by two participants. It is worth noting that while the other participant did not directly mention ice condition and ice class as important features, they did use them while formulating the basis of choice in Question 5. Zone of icebreakers, size of the vessels (i.e., are these technically good vessels), dirway location, and location of icebreakers with respect to vessel were other features that were singly mentioned by the participants.

Arguably, the most important piece of information needed to formulate the decision (Question 3, Table 1), two participants mentioned ETD of the vessels. The other participant identified ice condition as the most important information.

The question regarding gaps in the provided information (Question 4, Table 1) was appreciated by the participants. The most critical information that was identified to be missing was the wind information. The wind direction, strength, and pressure dictate the dynamic ice condition (such as ice drift). Two participants mentioned that based on the wind information one may almost have a new ice chart. In practice, with access to Icebreaker Net (IBNet), the icebreaker captains can create this new ice chart. The wind information along with the temperature also dictates how quickly or slowly a new channel will close. Port information (such as port calls and berthing availability) was missing, and it was also identified as a critical information.

While the use of ice chart was deemed okay, it was mentioned by the participants that in real life the captains will have access to satellite images through IBNet. In the absence of IBNet, it was suggested that instead of using a static ice chart, several ice charts (perhaps from a few days before) should be provided. The icebreaker captains also have access to fairway traffic information including how frequently the fairway been visited in recent time. This helps to identify if the ice in the fairway is new, recently broken, or has hardened over time. The nature of assistance is affected by this information. Other missing information includes assistance restriction on certain ice classes for certain ports, history of a ship for this winter: is it a frequent caller (already have a history on how they have been assisted this winter), ice field updates and other records from pilots put in the IBNet, records of phone calls to pilots, more specific vessel details such as propulsion power and hull type. The captains also have access to past tracks (knowledge of icefields, where channels have been created), and in-field information about the location of difficult spots in ice.

The last question was about the basis of choice where participants were asked to develop a rule to assist another person to make the same decision successfully (Question 5, Table 1). There is some similarity in the rules that participants 1 and 2 developed. The first step for both participants was to identify the vessels in each icebreaker zone that may require assistance. Vessel ice class and prevailing ice condition was used to assess the assistance requirement. Participant 1 also mentioned that for vessels in port, we know how they have been able to get there so chances are that they will be able to get out in similar manner with similar assistance requirements (depending on fairway situation). Then within each IB zone, participant 1 proposed using a first come first serve rule. This participant mentioned including incoming traffic while doing this. Participant 2 proposed choosing a vessel in need that is closest to the icebreaker. This participant added that the ETD of the assisted vessel dictates icebreaker's own departure time. Icebreaker will adjust its own engine power based on the departure time. If there is time, there is no need to go full throttle. Icebreakers will meet the vessels as close as possible to the point at which it is likely to be needing assistance. The goal is to minimize icebreaker movement.

Participant 3 had a bigger picture perspective based on choice. For non-critical situations, the participant had a rule to focus on minimizing the waiting time. The participant pointed out "[As IB captain] You have zones, you know each other, you know vessels in your zone, and you know the incoming traffic." Based on this, the waiting time minimization can be done. For safety critical scenarios like having high ice pressure, the participant advised to prioritize safety over minimizing waiting time. As mentioned by the participant "It takes guts to make safe decision since you may be increasing cost and waiting time."

Table 3. Basis of choice: rules provided by participants

Parti-cipant	Rule
1	First use vessel ice class and prevailing ice condition to decide who needs assistance. For each IB zone, follow first come first serve. Look at incoming traffic in the zone.
2	The ice condition (at departure time) and vessel ice class suggest where vessel might get stuck. Then the IB chooses the one that that is closest to its own location. Vessel ETD dictates IB's own departure time. Adjust engine power based on dept time. Meet the vessel as close as possible to the point at which it is likely to be stuck.
3	If you don't have any pressure, focus on minimizing the waiting time. If there is pressure, prioritize safety. It takes guts to make safe decision since you may be increasing cost and waiting time.

The basis of choice and the rules provided by each participant are presented in Table 3.

3.3 *Credibility of the scenarios and suggestions for improvement*

Question 4 reveals the information that are important for assistance decision making but were missing from the scenario description. The participants suggested that discussion on this should be continued as it is possible to include at least some of the missing information quite easily. They offered to help in increasing the credibility of the scenario. Besides the identified missing information, all participants mentioned adding a 3rd icebreaker to the South to make the scenario more realistic. One participant mentioned the missing wind information as critical and had to assume a wind direction to proceed with the scenario. This participant also evaluated the dirways to be unrealistic. This is because although the current location of dirways is set in easier ice conditions, it is too close to the shore. In practice, dirways are located further away from the shore, even if it means breaking channels in harder ice. This is to prevent grounding incidents. The participant suggested to refer to IBNet data and consult with experts in drawing dirways for future scenarios.

4 POTENTIAL APPLICATION OF THE RESULTS

Icebreaker decision-making is an important and elusive piece of the winter navigation operations that greatly affects its efficacy. The outcome of this study is expected to increase the realism of the ice-breaker behaviour in the simulation tool developed by Aalto University in close co-operation with the Finnish Transport Infrastructure Agency. This will enable realistic evaluation of several "what-if" scenarios, including engine power and ice-breaker scheduling optimization for safe, efficient, and environmentally friendly winter navigation. The outcome of the study will also contribute to developing intelligent systems that will support decision making for winter navigation. Given the nature of this study and the necessary detailed documentation, the results are also expected to generate educational materials, which can be used for training less experienced decision-makers and seafarers. The results are also expected to bring transparency to a process that has otherwise been hard to understand for those not directly involved in it. This could lead to better trust overall in the navigation environment and facilitate healthier cooperation between all stakeholders.

5 CONCLUSIONS AND FUTURE WORK

This paper describes a novel attempt at using CDM to decipher the complex icebreaker decision-making process. A pilot study was conducted to test the efficacy of this approach in this problem domain. The study involved subject matter experts in winter navigation. The results brought forth multiple interesting facets of the decision-making process that were hitherto unidentified by prior research efforts. The participants also gave several important inputs on how the scenarios can be improved for more directed knowledge elicitation. The future work will involve conducting a full-scale study with a larger number of participants with inter-rater reliability analysis and with refined operational scenarios that are more comprehensive and more realistic.

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