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Using Process Modeling Approach and Qualitative Data to Build a Unified Understanding of Icebreaker Operations

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Icebreaker operation is critical to maritime operations in ice-covered waters, as it contributes to the navigation safety and efficiency. However, the complexity of icebreaker operations, due to the challenging operational environment and the involvement of multiple components, remains largely undocumented. This lack of documentation has led to a limited understanding of the processes and missed opportunities for analysis and optimization of the operations. To address this gap, this study serves as a pilot for modeling icebreaker operation processes by leveraging data from a 10-day expedition onboard an operational icebreaker in the Baltic Sea. Through observations and interviews with expert crew members, the study identifies key activities, events, data resources used in decision-making, and workflows. The icebreaker operations are modeled using Business Process Model and Notation (BPMN) to represent the sequence of events, key activities, and decision-making processes. The formalized process model provides a structured representation of icebreaker operations, serving as a foundation for optimizing workflows, designing simulation models, automating decision-making, enhancing crew training, and supporting further analysis and research. This model can help to improve safety, reliability, and efficiency in ice-covered waters, while also supporting real-world applications and research that depend on precise process documentation.
Keywords: Icebreaker Operations, Business Process Modeling, BPMN, Decision Making, Qualitative data, Winter Navigation

1. Introduction

Icebreaker operations play a crucial role in maintaining safe and efficient maritime transport in ice-covered waters. These specialized vessels ensure the continuity of shipping routes during harsh winter months by breaking through ice to create navigable pathways for commercial and research vessels. As ice retreats, maritime traffic is expected to increase, leading to a growing demand for better understanding and optimizing icebreaker operations.

However, the inherent complexity of icebreaker missions, characterized by unpredictable environmental conditions and intricate operational procedures, poses significant challenges for documentation and analysis. Hence despite their importance, there remains a lack of comprehensive studies that formalize the intricate processes involved in icebreaker missions. This knowledge gap hinders efforts to enhance safety, efficiency, and sustainability in ice navigation.

Investigating the trend of previous research shows the importance and potential of operational modeling in operational improvement and efficient decision making in winter navigation. Some studies such as Smith et al. (2018) have highlighted the potential of "ship operational modeling" to enhance decision-making and operational efficiency in complex maritime environments. So, our hypothesis is that by understanding and formalizing icebreaker operational processes using graphical visualization and modeling, improvement of its operations and the efficiency of training can be facilitated.

Moreover, icebreaker operations have been the focus of various studies associated with navigating ice-covered waters. However, less attention has been given to comprehensive modeling of the whole process. Among them, Boström et al. (2018) employed a Work Domain Analysis (WDA) to systematically describe the broad array of tasks performed on board icebreakers. The main contribution of the mentioned study is to provide a systematic description of icebreaker operations. However, while the study provides valuable insights into the broad tasks and constraints of icebreaker operations, it lacks a detailed representation of workflows, decision-making processes, and the interrelation of activities.

Decision-making in icebreaker operations is another studied area. There are limited numbers of studies dedicated to the decision-making in icebreaker operations. Musharraf et al., (2023) conducted a pilot study to explore decision-making strategies for prioritizing icebreaker services using the Cognitive Task Analysis (CTA) method. Liu et al., (2024) investigated how the need for icebreaker assistance can be estimated through data-driven analysis. While these studies provide comprehensive insights into individual decision points, they do not offer a complete model of the entire icebreaker operation process.

With the growing trend toward automation in maritime industries, researchers have begun exploring how icebreaker operations can be digitized and automated. One approach that has been applied in this area is the Functional Resonance Analysis Method (FRAM), which has been used to model ice management operations and identify key features required for machine learning and autonomous systems (Musharraf et al., 2022). Using FRAM, the research provides a transparent understanding of icebreaker operations with focusing on expert knowledge digitization.

Although previous research has shed light on certain aspects of icebreaker operations, these studies tend to focus on modeling tasks in isolation and a holistic model of the entire process systematically capturing the sequential flow, dependencies, and interaction of processes is lacking.

In parallel, models such as the FRAM and the Systems-Theoretic Accident Model and Processes (STAMP) offer valuable insights into the dynamic interactions and emergent behaviors in complex systems for analyzing risks and safety management (Salihoglu & Bal Beşikçi, 2021; Valdez Banda et al., 2019; Viran & Mentes, 2024). Basnet et al. (2019) highlight that such systemic models provide a comprehensive framework to understand non-linear interdependencies and dynamic interactions in safety-critical environments. However, one notable limitation is that while such models excel in capturing systemic interactions, they do not explicitly model the detailed sequence of tasks and decision gateways inherent to operational procedures.

This gap is significant in contexts where the precise ordering of activities and critical decision points is essential for aligning work-as-done with work-as-planned. Consequently, there is a need to complement these systemic models with approaches that can provide a detailed representation of process sequences, ensuring a more comprehensive understanding of operational workflows and enabling more effective risk mitigation.

This study addresses these challenges by conducting a pilot investigation that employs Business Process Model and Notation (BPMN) (OMG, 2014) to create a detailed and structured representation of icebreaker operations. BPMN is a well-established systemic modeling framework widely used across industries to visualize complex processes in a way that is both accessible and analytically rigorous. Its ability to represent workflows through standardized diagrams makes it particularly suited for capturing the intricate tasks, decision points, and interactions that define icebreaker missions.

Recent studies in air and marine navigation suggest that employing business process modeling (BPM) can offer a comprehensive overview of operations and processes, leading to more efficient operational and strategic planning, improved decision-making systems, and enhanced risk assessments (Akan, 2023; Böhm et al., 2022; Mhand et al., 2018; Rott et al., 2023; Saragiotis, 2019; Veenstra & Harmelink, 2022). This research utilizes BPMN to develop a detailed process model that not only formalizes icebreaker operations but also serves as a foundation for identifying inefficiencies of operations, improving training protocols, and integrating automated decision-support systems.

The foundation of this research is grounded in qualitative data collected during a 10-day observational study onboard an operational icebreaker in the Baltic Sea. Through a combination of direct observations and interviews with expert crews, the study captures the key activities, events, and the data resources involved in operation process. These findings have been formalized into a BPMN model that accurately reflects the sequence of activities, triggers, gateways, and decision-making processes.

By enhancing the understanding of these complex processes, the model can be used as a preliminary step for risk management and operational optimization. Additionally, it could support real-time decision-making, optimize resource allocation, and improve icebreaker coordination, ultimately strengthening operational safety and effectiveness in ice-covered waters.

2. Method

To develop the proposed method for transforming textual qualitative data into BPMN models, we built upon existing research on qualitative data analysis. Qualitative data helps deepen our understanding of processes, systems, and behaviours. However, analysing such data can be complex and must be done systematically to avoid common pitfalls. These include risks like misrepresenting data due to cognitive biases and overlooking critical information due to the complexity of the data.

Our approach is grounded in a previously established method (Law et al., 2023) which consists of three steps: segmentation, classification, and modeling, enabling us to create a concrete process specifically designed for transforming qualitative data into BPMN models. In this paper, we adopted these three steps but modified their rules to better align with the scope and nature of icebreaker operation processes. This structured method helps in minimizing cognitive biases of qualitative data into BPMN models.

The segmentation and labeling process are designed to extract meaningful tasks and subtasks from qualitative data. To improve clarity and reduce redundancy, rules should be applied hierarchically. By consolidating the rules and focusing on high-priority indicators, this approach leads to more accurate model. The following subsections describe the three main steps of BPMN modeling in detail.

2.1. Segmentation

At this step, the qualitative data is divided into smaller segments using linguistic cues. Verbs correspond to tasks or events, but some expressions provide context (like time, conditions, or clarifying details) rather than actions. The segmentation step aims to identify segments that describe main tasks, subtasks, and other key BPMN elements. Granularity can vary between modelers, so smaller segments are preferred to avoid losing or mixing information. Table 1 provides a detailed description of the segmentation rules.

Table 1. Segmentation rules and their descriptions

Segmentation Rules
1. The presence of a verb:
Verbs often indicate actions and should trigger a new segment. This includes broad actions (potential Main Tasks) and more specific actions (potential Subtasks).
2. The presence of a phrase that includes gerunds (verbs in their -ing form):
Phrases containing gerunds often describe actions or tasks that should be identified as segments.
3. Finer segmentation to capture all elements:
If a task or subtask is described with several actions or details, break them into smaller segments to ensure clarity and granularity.
4. Non-task segments:
Time-related, condition-related, or descriptive clauses that don't represent an action should also be segmented. These will be labelled appropriately in the labeling step.
5. Clauses that provide extra information:
Relative clauses, adjective clauses, or other clauses that provide more information on a subject should be segmented separately to avoid blending tasks with descriptions.

2.2. Labeling

At this step, each segment identified in step 1 is labelled into one of the eight classes: Main Task (MT), Subtask (ST), Secondary Subtask (SST), Setting (S), Annotation (Aref), Event (En), Condition (C), or Other (On). This labeling is based on BPMN elements but adapted to the specifics of the data. The goal is to assign BPMN-related roles based on the nature of the segment. This step ensures that the text is interpreted consistently, avoiding the introduction of personal biases. Table 2 provides a detailed explanation of the labeling rules.

Table 2. Labeling rules and their descriptions

Labeling Rules
1. Main Task (MT):
A Main Task (MT) is identified by a broader activity that governs the process and are typically identified by verbs or phrases indicating high-level activities.
2. Subtask (ST):
A Subtask (ST) is identified by a specific action that supports the Main Task. It is often embedded within or follows a Main Task, describing more detailed actions.
3. Secondary Subtask (SST):
If a Subtask contains additional, specific actions (more granular than the subtask itself), classify those as Secondary Subtasks.
4. Sub-process
If any of these activities involve a series of steps that form a distinct, repeatable unit with internal decisions or subtasks, classify them as sub-process
5. Setting (S):
Descriptions of the situation, time, location, or emotional state surrounding the tasks.
6. Condition (C):
Describes alternatives or time-dependent conditions.
7. Event (En):
Incidents that occur in the environment. These could also include actions by other actors or time-related incidents.
8. Annotation Reference (Aref):
Additional or clarifying information related to a task, event, or condition.

2.3. Modeling

Finally, the labeled segments are converted into BPMN elements. Tasks, Events, and Conditions are directly translated into BPMN graphical components as stated in (White, 2006), such as tasks, boundary events, and gateways. Other classes, such as Setting and Annotation can be added as supplementary notes in the BPMN diagram. Table 3 provides a detailed explanation of the modeling rules and their graphical representation.

Table 3. Modeling rules and their descriptions

Modeling Rules
Events
1. Start Event: Start Event triggers the process.
2. Intermediate Events (En) These events occur during the process and represent points where something happens that affects the flow.
3. Boundary Events (En+): • **Interrupting Boundary Events:** The task stops when the event occurs. • **Non-Interrupting Boundary Events:** The task continues while the event occurs.
4. Message Event It indicates sending or receiving a message.
5. Timer Event (interrupting, non-interrupting) Timer events triggered by specific timing.
6. End Event: Every process ends with an End Event.
Activities (Tasks):
7. Main Task (MT): A high-level action that represents a primary activity rectangle.
8. Subtasks (ST) and Secondary Subtasks (SST): Represented as an activity/task rectangle, like MT, but smaller in size or shown in a nested structure.
9. Sub-process: Represented with a "+" symbol. This signifies that the task contains a detailed, decomposed set of steps or activities.
10. Looped Task: It repeats until a specified condition is met.
Gateways: Used for Conditions (C)
11. Exclusive Gateway (XOR): Represents a conditional path where only one option is chosen.
12. Parallel Gateway (AND): Represents tasks that can be executed simultaneously or joined after completion.

3. Case Study

3.1. Qualitative data collection

Since this study serves as a pilot for modeling the icebreaker operation process, the data collected includes observations and expert interviews from a 10-day expedition. The observational data consist of detailed notes on operational practices, such as ice condition monitoring, assessing the need of icebreaker assistance, interactions among different components of the winter navigation system, and encountered environmental conditions. These observations are recorded to capture the complexity of icebreaker operations in situ.

To conduct the expert interviews systematically, a semi-structured format was designed. The Critical Decision Method (CDM) was employed to develop the interview questions. Due to the extensive nature of the CDM method, a detailed description is omitted here. The readers are referred to (Musharraf et al., 2025) for more information. The interview participants consisted exclusively of officers stationed on the icebreaker bridge, as they are responsible for the vessel's daily operations. These participants had between 15 and 43 years of maritime navigation experience, with a minimum of 6 years of experience navigating in ice.

3.2. Applying 3-steps method and result

The proposed 3-step methodology was applied to the qualitative data collected through observation and interview tasks. Table 4 illustrates the results of the segmentation and labeling steps, providing an example of how the rules were applied to a sample dataset. In developing this model, we have applied the BPMN graphical representations outlined in Table 3, including exclusive gateways to represent decision points and parallel gateways to denote concurrent tasks, and the labeling terminology from Table 2 for identifying Main Tasks (MT), Subtasks (ST), and Events (En). This structured approach not only documents the operational steps but also provides a robust basis for analyzing potential failure points and communication bottlenecks, thereby enhancing reliability and safety in ice-covered waters.

Figure 1 depicts the overall process of icebreaker operations using the BPMN framework. The model is structured into two primary lanes, Merchant Ships and Icebreaker, to illustrate the interactions between these entities. The process includes 5 main tasks, two of them are modeled and represented as subprocess: “Leaving Port” (MT), “Navigation to Position” (MT), “Staying Still” (Sub-process), “Assisting Vessels” (Sub-process), and “Returning to Port” (MT). The operations begin with the icebreaker departing the port and navigating to its designated position. Upon reaching its position, the icebreaker enters a "Staying Still" subprocess (detailed in Figure 2), a critical segment where the icebreaker remains stationary to perform continuous assessments

Table 4. An example for segmentation and labeling on a sample part of data

A sample part of data	Traffic condition monitoring: Connection with the pilot systems – when the IB stays in the fairway to track inbound/outbound vessels and track which vessel would need help and when. Observation - About the vessels in the sea. IBNET also has traffic information and detailed ship operation for specific ships
Results of applying Segmentations and Labeling Rules	Traffic condition monitoring: (MT) Connection with the pilot systems – (ST) 3. when the IB stays in the fairway (S) 4. to track inbound/outbound vessels (SST) 5. track which vessel would need help and when (SST) 6. Observation – (ST) 7. About the vessels in the sea (Aref) 8. IBNET also has traffic information (ST) 9. detailed ship operation for specific ships (SST)

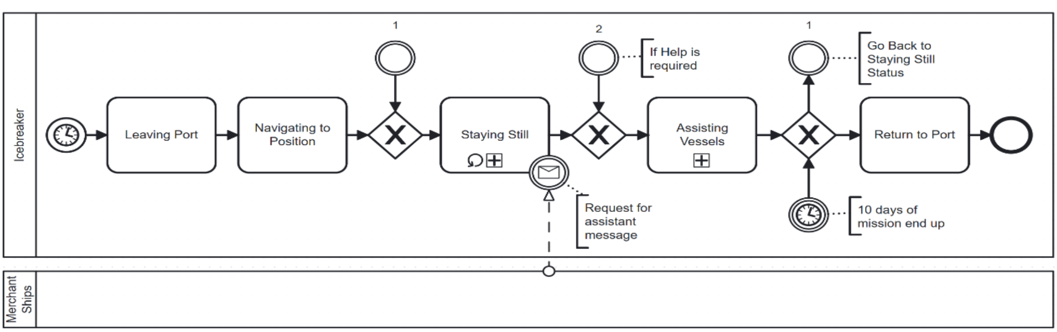

Figure 1. the The BPMN model of the core process of the icebreaker operations

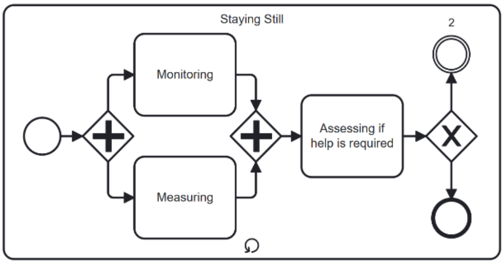

Figure 2. The BPMN model of “Staying still” subprocess with more details.

In accordance with the labeling rules presented in Table 2, this phase is broken down into three main activities:

- “Monitoring” (MT) – Defined as a Main Task, this activity involves the continuous observation of ice movements, weather conditions, and nearby vessel activities using onboard sensors and external communication systems. This task ensures that real-time environmental changes are captured, forming the basis for proactive risk management.
- “Measuring” (ST) – As a Subtask (ST), this activity entails the systematic collection of quantitative data such as ice thickness, compression levels, and environmental factors. These measurements provide objective data that complement the visual observations, enhancing the accuracy of risk assessments.
- “Assessing if Help is Required” (Decision Gateway) – Leveraging the data gathered from Monitoring and Measuring, this step modeled as an exclusive gateway, represents the decision-making process. At this stage, the system evaluates whether the current conditions warrant intervention. If no assistance is required, the process loops back to Monitoring and Measuring; otherwise, it transitions to the vessel assistance phase.

If no help is needed, the process loops back to the "Staying Still" phase, where Monitoring and Measuring continue. But, if help is required, the icebreaker transitions to the "Assisting Vessels" subprocess (detailed in Figure 3).

The subprocess comprises several interconnected components:

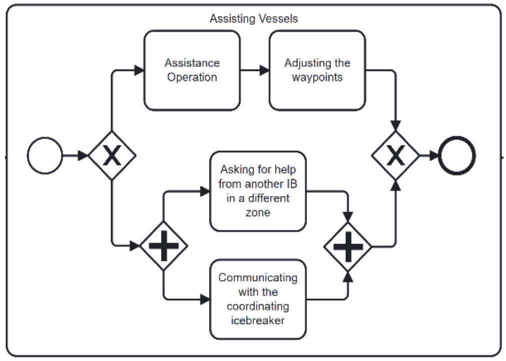

Figure 3. The BPMN model of “Assisting Vessels” subprocess with more details.

- “Assistance Operations” (MT) – As a Main Task, this activity involves the icebreaker engaging in direct intervention—such as clearing ice, creating navigable pathways, or escorting vessels—to mitigate identified risks.
- “Adjusting the Waypoints” (ST) – This Subtask involves dynamically modifying routes for the icebreaker and the assisted vessels based on real-time environmental data. It is a critical step to ensure that navigation remains safe under evolving conditions.

In cases where the icebreaker itself cannot address the assistance request; the icebreaker may proceed to:

- "Asking for help from another icebreaker in a different zone" to coordinate broader assistance efforts.
- "Communicating with the coordinating icebreaker", ensuring effective collaboration among operational units.

Once “Assistance Operations” are completed, the process either cycles back to the "Staying Still" phase or, if the mission timeline nears its end, transitions to "Return to Port". The process concludes with the icebreaker returning to its base after completing its tasks or upon reaching a "10 days of mission end up" milestone, signalling the closure of operations. This cyclical process ensures continuous monitoring, decision-making, and operational conditions flexibility throughout the icebreaking mission.

By using systemic modeling, such as BPMN, it becomes possible to visualize the sequence of events leading to delayed interventions, identify bottlenecks in communication or resource allocation, and propose procedural adjustments that ensure faster and more effective decision-making. This type of structured process representation can be served as a preliminary step in risk management, as it allows for a clearer understanding of how real-time constraints and decision-making delays may contribute to operational hazards. A systemic representation of this process enables identification of communication gaps, procedural inefficiencies, and resource misallocations.

For example, the Delayed Intervention Decision (Decision Gateway) represents a critical decision point where a postponed assistance response can increase the risk of ice entrapment for vessels. Similarly, the Requesting Additional Icebreaker Support (Message Event) highlights the importance of timely coordination between multiple icebreakers. If communication between vessels is delayed or inefficient, operations may face further setbacks, increasing the risk of navigational congestion and prolonged disruptions.

4. Discussion and Conclusion

This study presents a pioneering effort to model icebreaker operations using a structured, process-driven approach. Leveraging qualitative data from a 10-day Baltic Sea expedition and expert interviews, we formalized key operational phases, namely "Navigating to Position," "Staying Still," and "Assisting Vessels", into a comprehensive BPMN model that captures dynamic workflows and decision-making processes. Notably, the "Staying Still" phase serves as the central hub, where continuous monitoring and measurement provide critical situational awareness and feed into decision gateways that determine if intervention is necessary.

The outlined BPMN model offers a systemic representation of the existing operational procedures in icebreaker missions. This transparent picture opens pathways for automation, performance optimization, and enhanced resource allocation. The model also highlights the crucial role of communication and coordination between vessels, bridging the gap between work-as-planned and work-as-done.

This detailed visualization of process elements, such as decision gateways, parallel tasks, and communication events, can aid in generating actionable insights for future safety assessments and risk management. It can optimize operational efficiency and improve emergency preparedness, leading to safer winter navigation. Moreover, the formalized model can be integrated into a tool for training programs, enabling crews to better understand and navigate the complexities of ice-covered environments.

As this study is a pilot investigation conducted on a single icebreaker and based on limited observational data, its results should not be generalized without further validation through a comprehensive full-scale study. Building on this work, future research should focus on refining the model with expert feedback and integrating real-time data sources, such as AIS and environmental sensors, to enhance its accuracy and enable dynamic simulations and real-time decision-making tools for complex maritime environments.

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