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Using the FRAM to Understand Arctic Ship Navigation: Assessing Work Processes During the Exxon Valdez Grounding

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ABSTRACT: Arctic shipping involves a complex combination of inter-related factors that need to be managed correctly for operations to succeed. In this paper, the Functional Resonance Analysis Method (FRAM) is used to assess the combination of human, technical, and organizational factors that constitute a shipping operation. A methodology is presented on how to apply the FRAM to a domain, with a focus on ship navigation. The method draws on ship navigators to inform the building of the model and to learn about practical variations that must be managed to effectively navigate a ship. The Exxon Valdez case is used to illustrate the model's utility and provide some context to the information gathered by this investigation. The functional signature of the work processes of the Exxon Valdez on the night of the grounding is presented. This shows the functional dynamics of that particular ship navigation case, and serves to illustrate how the FRAM approach can provide another perspective on the safety of complex operations.

1 INTRODUCTION

The Arctic may become integral part of the shipping industry on a global scale if current climate trends continue. If that does happen it will involve a transitional period, where many lessons will be learned as the boundaries of normal shipping operations are broadened. Experienced shipping in the Arctic is limited, information is scarce, and not widely shared. In order to become prepared for such an increase in shipping traffic in the Arctic (and Antarctic), information we do have should be examined as thoroughly as possible. This may help us better understand the conditions and how to operate in them.

The present work uses the Functional Resonance Analysis Method (FRAM) to build an understanding of Arctic ship navigation and uses the Exxon Valdez grounding as a case to examine the model's utility. This work is intended to initiate discussion across the maritime domain about FRAM and understanding Arctic operations. We can use the FRAM to help understand different elements of ship navigation, including the so called "soft factors," which are difficult to assess with traditional techniques. This will become even more important when considering Arctic shipping because the information is both vague and scarce (Arctic Council, 2009). The FRAM provides a structured framework to consider anecdotal experience from successful shipping operations, which can help formalize lessons learned and share them across the domain. By consolidating information across the domain it will improve our understanding of shipping safety. By improving our understanding this way, we can then improve ship operations (the way they function) and safety in the maritime domain.

2 BACKGROUND

A shipping operation is a socio-technical system that requires many combinations of social and technical factors to be managed to succeed. There has been a movement towards adaptive approaches to safety to help manage such systems (Borys et al., 2009). This approach relies on not only modeling the elements in the system, but the relationships in the system, eg. how elements interact together (Vicente, 2004). Because of this shift in thinking, other techniques are being adopted from resilience engineering to help manage complex systems as well (Ayyub, 2015, 2014; Hollnagel et al., 2006).

Additionally, there is acceptance that many of the conditions that operations are being subjected to are so dynamic that it is very difficult to prescribe a single safety protocol to manage them. The Society of Risk Analyst's recent review states that in these cases it is better to have a dynamic set of solutions to adapt to these dynamic conditions (Aven et al., 2015). Safety is then approached by understanding how to best monitor areas of the system and how to control them: in other words, by designing systems that adapt (or maintain control) when subjected to dynamic conditions.

There are a number of methods that are founded on adaptive safety methodologies: the Functional Resonance Analysis Method (FRAM), Systems-Technical Accident Model and Processes (STAMP), and Human-Tech approach (Hollnagel, 2012; Leveson, 2004; Vicente, 2004, respectively). Each method has the potential to improve safety by incorporating systems thinking into the approach. In this paper the FRAM is used to perform an investigation of ship navigation in the Arctic. The FRAM was chosen for two reasons: 1) it focuses on functionality, and 2) it promotes communication between assessors and workers. To understand functionality, you must understand the conditions that can be operated in, and the conditions that cause problems. This means that accident events should not be isolated from the typical operational outcomes to develop understanding of accident mechanisms. By isolating the accidents, biases may enter the interpretations of events. Safety solutions should show consideration of both the event(s) one would like to prevent and promotion of the event(s) one would like to achieve. When understanding functionality, it is best to obtain an understanding from the operational perspective. This concept promotes understanding the work as it is done, rather than as it is imagined by assessors. This can help reduce the communication gap that exists between assessors and operators, thereby, promoting safety solutions that are grounded in reality.

2.1 *FRAM*

The FRAM is built on identifying functional resonance. Functional resonance is an analogy to stochastic resonance, where multiple signals of low amplitude noise are inputted to a system and, if resonance occurs, the overall system signal can have a much greater amplitude. In functional resonance, the output of the system functions are variable and slight variations between the many functions in a system have the potential to combine in such a way that resonance occurs. The resonance will be some variation of the overall system performance that goes beyond what is typical or expected, regardless of whether the outcome is viewed as good or bad. By modeling the system functions and variability in sufficient detail, safety solutions will emerge that focus on monitoring and controlling the system.

The FRAM is based on four underlying principles (Hollnagel, 2012):

- Failures and successes are equivalent in the way that they happen for the same reason. Alternatively, it can be said that things go wrong for the same reasons that they go right.
- Daily performance of socio-technical systems, including humans individually and collectively, is always adjusted to match the system conditions.
- Many of the outcomes of the system that we notice, and also the ones we don't notice, are emergent rather than resultant.
- Relations and dependencies must be described as they develop in a particular situation and not as cause-effect links. This is done through functional resonance.

The first step of the FRAM is to describe the functions of the system and the aspects of the functions that occur when work happens. Each function can have 6 aspects that should be considered, as seen in Figure 1.

Output: Each function should have an output(s). If work is being done there should be something produced by the work. The outputs are then passed throughout the system and have the ability to affect other work in the system in 5 possible ways.

1. Input: The input starts the functions. If the input is an output that arrives late from another function, it will affect the functionality of the downstream function.
2. Preconditions: Preconditions must be available prior to the function starting, but they do not initiate the function. They can lay dormant in the system until the function begins.
3. Resources: These are things that are processed during the function. To limit the resources that considered, focus should be placed on resources that are consumed and subsequently need to be resupplied by another function in the system. Resources such as computers, which are not consumed, should not considered here. They would be considered as execution conditions, which can be assessed when understanding the function itself.
4. Time: Other functional outputs have the potential to affect the available time to carry out a function.
5. Control: Other functions may interact with downstream functions in a way that acts as a control.

After the system functions and aspects are described at some level of detail. The variability should be considered. Step 2 considers the internal variability of the function and the variety of ways an output can be produced under dynamic conditions. Step 3 assesses the coupled system variability, which is the way the variations from upstream functions can affect the downstream functions, and in turn the entire system performance. The final step is to identify appropriate ways to monitor the system and control the variability in it. In practice, it is very difficult to obtain all the necessary information at once, so this process may need to be repeated as new information is obtained.

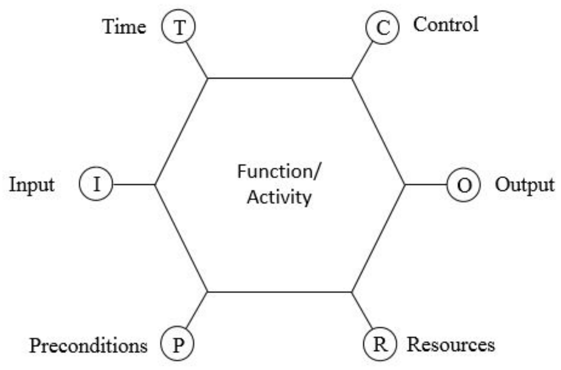

Figure 1. FRAM function diagram (Hollnagel, 2012)

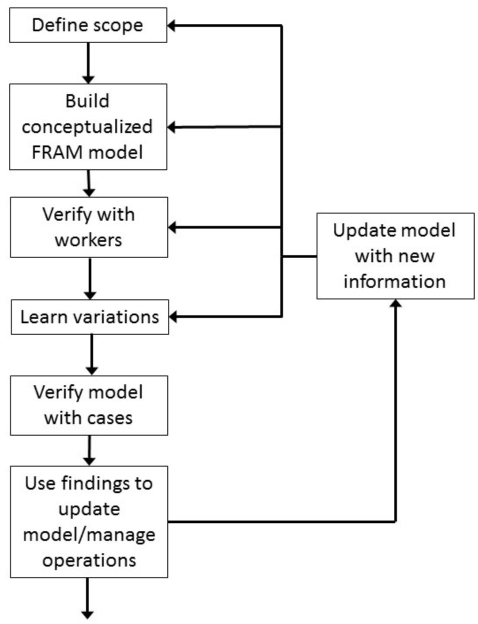

Figure 2: Methodology for building FRAM model

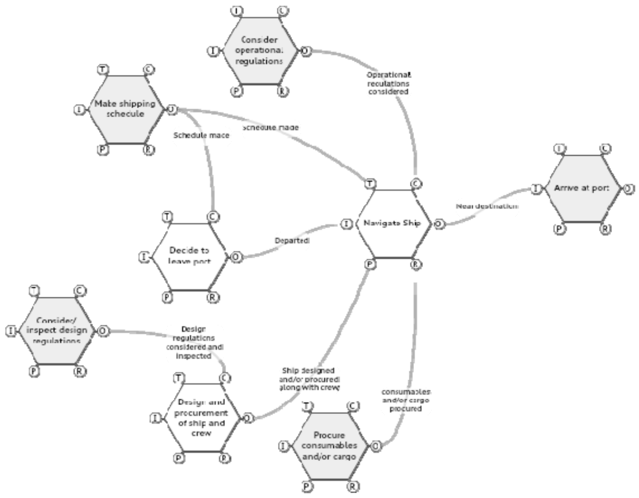

Figure 3: General ship navigation FRAM model (scope)

3 METHODOLOGY

In order to build a FRAM model for Arctic ship navigation the following methodology was used. First, the scope was defined. Then the system functions and connections were imagined by the assessor(s). The conceptualized model was then checked with operators to verify that the model reflects the way the work is actually done. At this point, the model represented the potential functional paths that could be taken for the system to produce some outcome. Then the variability of the functional outcomes can be understood. It is best to learn about the variability of the functions by either monitoring the functional output directly or communicating with the workers who carry out each function. Once the functional model was built and some variability documented, the model was applied to cases. By examining cases through the lens of the FRAM, different findings may emerge that pertain to functional execution and system variability. These findings can then be used to either update the model, or manage the operation. This methodology is mapped out in Figure 2.

3.1 *Defining the scope*

The first step is to define the scope of the assessment. This assessment focuses on (Arctic) ship navigation. From a systemic perspective, there are many functions that influence the performance of a shipping operation and trying to model all of them at once could be overwhelming. As there is so much information to learn about the work that is carried out in a shipping operation, the initial assessment focuses on navigating the vessel. This is the most basic objective for a ship and all other work is complementary to it. This allows the initial understanding to reflect the most immediate functions required for navigation, and then the scope can be gradually broadened in the future. Also, the focus will be on transit shipping; stationary offshore installations are out of scope.

First, build a FRAM model to help define the scope (Figure 3). We define a function, “Navigate ship,” which describes the function that is carried out to physically move the ship from port to port. Then we can define the aspects of the “Navigate ship” function. The output can be that the ship is now near the destination, and other functions involved in, “Arrive at port,” can begin bringing the ship to the destination. The input is the function “Decide to leave port.” While this decision to leave is influenced by the shipping schedule, the ship does not necessarily leave exactly when scheduled. Many factors could affect the time at which the ship actually leaves port, but this decision is controlled by the schedule. The time that this decision will be made will be roughly around the scheduled time, but could be ahead or behind schedule, due to inspections, cargo or consumable loading, etc. The shipping schedule can also influence the ship navigation function with respect to time. The ship navigator may make decisions to speed up or change route to stay on schedule. A major controlling aspect for ship navigation is to “Consider operational regulations.” By considering these operational regulations, best practices, and guidance can be transferred to the ship navigator, helping to control the functionality. A precondition is that a ship must either be designed and/or procured and crew must be hired in order to navigate this ship. This is a precondition because it must happen prior to the ship navigation, but it does not initiate the ship navigation as the input does. The ship and crew can remain at port until the decision to leave port has been made, then "Navigate ship" can begin. Lastly, let's consider the resources necessary to navigate a ship. In the FRAM, resources should be focused on items that are consumed during or need to be resupplied after a function is executed. While, we could think of the ship as being a resource, it will not be consumed (at least not over a single voyage), and is more appropriately considered as a precondition aspect. Resources such as cargo and consumables (fuels, stores, ballast, maintenance materials) will be consumed during a voyage and should be resupplied before another voyage is to begin.

This generalized model (Figure 3) has helped us define scope and start thinking about ship navigation in terms of the FRAM. However, the model is not yet detailed enough to provide much useful insight. Now that the scope is better understood, the focus can be shifted to understanding how ship navigation is carried out.

3.2 *Building a conceptualized FRAM model*

In the FRAM, it is best to have your assessment informed by the workers who carry out or interact closely with the system functions. However, it is useful to first build a conceptualized model from the perspective of the assessors to help illustrate the FRAM to the worker(s) in the context of their operation. This conceptualized model can be seen in Figure 4.

In Figure 4, the ship navigation process is described as a continual assessment of the conditions that result in a decision to maintain a course or to change course. This can be done many times over a single voyage. The decision then leads to the navigator following the chosen course and notifying the crew of any adjustments, if necessary. In order to reasonably make an assessment, the ship navigator must consider many conditions comprehensively to make the most informed decisions. The outputs from these functions may be produced at different rates and assessments by the navigator will be made with varying levels of information. Some of the inputs that we can imagine are important to a navigator's assessment are:

- Observing the current weather conditions
- Obtain weather forecasts
- Observe the ice conditions
- Obtain Ice forecasts
- Consider the intended or predicted route
- Monitor the condition of the vessel
- Be aware of the surrounding location and geography.

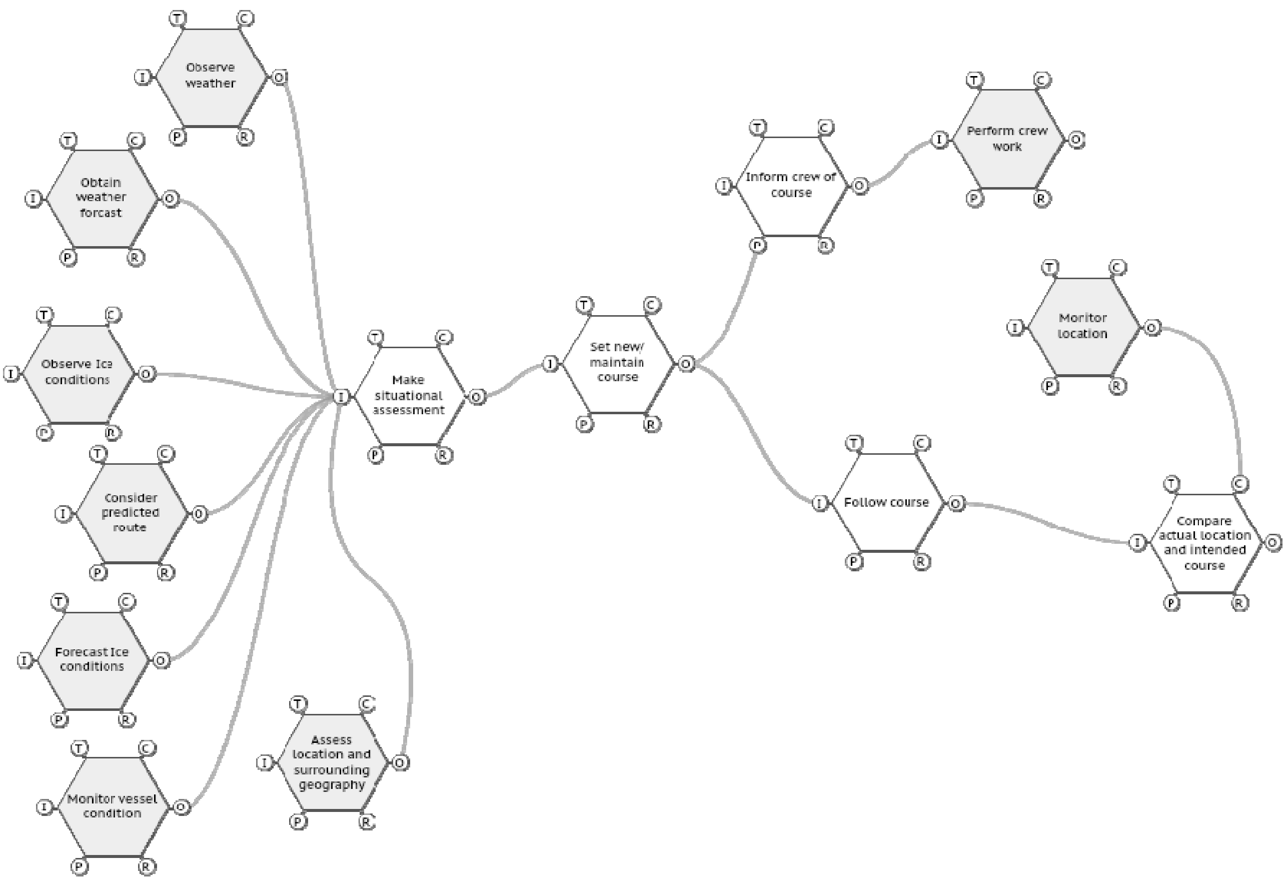

Figure 4: Conceptualized FRAM model for ship navigation

3.3 *Verifying with workers*

To inform our assessment, we spoke with 3 ship captains. The discussions were focused on understanding how ship navigators navigate ships, and making note of any unusual variations or conditions that they shared. The representation of ship navigation (Figure 4) was critiqued by the 3 ship navigators and it contained many of the functions that the navigators used but it was incomplete. Consider the functional descriptions and the initial description of the aspects for ship navigation in Table 1. The only times that an output will by omitted is when it has been left out to define the scope of the analysis. Similarly, when "not initially described" is listed, this does not mean that that aspect is not present. It means that the scope has initially been limited to describing the coupling of the immediate functions that have been described. This will help prevent becoming overwhelmed with complexity initially. Additional aspects can be further described later, if needed.

It can be seen that additional functions have been identified through conversations with ship navigators. The visual representation of the FRAM model with input from ship navigators can be seen in Figure 5. It can be seen that this more detailed description of ship navigation shows a more complex representation than the one in Figure 4. It is important understand the complexities that are present in ship navigation because these complexities must be managed in the operation, whether we decide to model them or not.

Table 1. Initial description of FRAM functions and aspects for ship navigation

Name of function	Obtain weather forecast	Set new/ maintain course	Observe Ice conditions
Description	Obtain weather forecast from meteorological organization or department	A decision is made to either maintain the current course or to make adjustments to course.	Observe the current ice conditions. This can be done from the bridge or on deck, but also the conditions ahead can be observed via helicopter or aircraft
Aspect	Description of Aspect	Description of Aspect	Description of Aspect
Input	Not initially described	Complete or partial assessment made	Not initially described
Output	Weather forecast obtained	Routing decision made	Ice conditions have been visually observed onboard Up route ice conditions assess. with Helicopter
Precondition	Not initially described	Not initially described	Not initially described
Resource	Not initially described	Not initially described	Not initially described
Control	Experience based weather judgement	Not initially described	Experienced visual assessment of ice Radar image observed
Time	Not initially described	Not initially described	Not initially described
Name of function	Forecast Ice conditions	Assess location and surrounding geography	Inform crew of course
Description	Obtain the forecasted ice conditions. This may be done by historical trends in area and/or tactical ice drift models	Locate the vessel with respect to intended route, shipping lanes and regional geographic features.	Inform crew of any change of course if necessary.
Aspect	Description of Aspect	Description of Aspect	Description of Aspect
Input	Not initially described	Not initially described	Not initially described
Output	Obtained forecasted ice conditions Daily ice chart observed	Geographical assessment made	Responsible crew member notified
Precondition	Not initially described	Aware of the present route	Routing decision made
Resource	Ice chart downloaded	Not initially described	Not initially described
Control	Experience based ice forecast	Have shipping lane maps Improved knowledge of regional specific conditions	Not initially described
Time	Not initially described	Not initially described	Not initially described
Name of function	Assess location and surrounding geography	Make situational assessment	Perform crew work
Description	Locate the vessel with respect to intended route, shipping lanes and regional geographic features.	The captain and bridge team make a situational assessment based on the available information at a given time.	The crew will perform their necessary work to maintain course or adjust their work to accommodate any changes.
Aspect	Description of Aspect	Description of Aspect	Description of Aspect
Input	Routing decision made	Weather forecast obtained Up route ice conditions assess. with Helicopter Obtained forecasted ice conditions Geographical assessment made Weather has been observed Aware of apparent vessel condition Ice conditions have been visually	Responsible crew member notified

		observed onboard Proximate traffic communicated with	
Output	Not initially described	Complete or partial assessment made	Not initially described
Precondition	Not initially described	Not initially described	Not initially described
Resource	Not initially described	Not initially described	Not initially described
Control	Not initially described	Ice Numeral computed	Not initially described
Time	Not initially described	Not initially described	Not initially described
Name of function	Observe weather	Consider predicted/updated route	Compute Ice Numeral
Description	The current local (ship) weather conditions are observed. This can be from the bridge or on deck.	Consider the current route you are transiting. This may be suggested by operational planners or adjusted by the navigator.	Compute the ice numeral as per Canadian regulatory requirements.
Aspect	Description of Aspect	Description of Aspect	Description of Aspect
Input	Not initially described	Not initially described	Daily ice chart observed
Output	Weather has been observed	Aware of the present route	Ice Numeral computed
Precondition	Not initially described	Not initially described	Ship classification assigned
Resource	Not initially described	Not initially described	Not initially described
Control	Not initially described	Not initially described	Not initially described
Time	Not initially described	Shipping schedule made	Not initially described
Name of function	Monitor vessel condition	Assign ship classification	Download daily ice charts
Description	The vessel's condition is monitored to understand the vessel's current capabilities.	The ship is assigned a classification. In particular, this classification here pertains to the category that will be used to compute the ice numeral.	Download the daily ice chart(s) that are applicable to your region. These charts are produced by Canadian Ice Services (CIS) in Canada.
Aspect	Description of Aspect	Description of Aspect	Description of Aspect
Input	Not initially described	Not initially described	Not initially described
Output	Aware of apparent vessel condition	Ship classification assigned	Ice chart downloaded
Precondition	Engine room maintenance/ issues informed Aware of vessel's typical capability	Not initially described	Not initially described
Resource	Not initially described	Not initially described	Not initially described
Control	Not initially described	Not initially described	Not initially described
Time	Not initially described	Not initially described	Not initially described
Name of function	Ice navigator makes assessments	Obtain map of shipping lanes	Observe radar image
Description	Ice navigator makes assessments of the conditions and upcoming tasks and shares experience with ships bridge team.	Prior to shipping through an area it is good practice to obtain maps of the shipping lanes. The shipping lanes typically has more reliable soundings and have been practiced over the years.	The radar image is observed and then should be visually inspected to determine what caused the radar image to be produced
Aspect	Description of Aspect	Description of Aspect	Description of Aspect
Input	Not initially described	Not initially described	Not initially described
Output	Experienced visual assessment of ice Experience based ice forecast Improved knowledge of regional specific conditions Experience based weather judgement	Have shipping lane maps	Radar image observed
Precondition	Ice navigator has been assigned	Not initially described	A radar signal has been detected by ships radar
Resource	Not initially described	Not initially described	Not initially described
Control	Not initially described	Not initially described	Not initially described
Time	Not initially described	Not initially described	Not initially described
Name of function	Observe other traffic	Communicate with proximate traffic	Communicate with engine room
Description	Observe any other shipping traffic that may be in the area	Communicate with proximate traffic. This can be done via lights, horns or radio.	There is communication between the engine room and the bridge to discuss any issues or needed maintenance.
Aspect	Description of Aspect	Description of Aspect	Description of Aspect
Input	Not initially described	Other traffic observed	Not initially described
Output	Other traffic observed	Proximate traffic communicated	Engine room maintenance/issues

		with	informed
Precondition	Not initially described	Not initially described	Not initially described
Resource	Not initially described	Not initially described	Not initially described
Control	Radar image observed	Not initially described	Not initially described
Time	Not initially described	Not initially described	Not initially described
Name of function	Assign certified ice navigator	Detect radar image	Become aware of vessel's capability
Description	To assign an ice navigator to assist with navigation of the vessel. This is required for Navigation in the Canadian Arctic.	Radar signal has been sent from ships radar and is ready to receive any signals that bounce back from objects	The navigator becomes aware of the vessel's capabilities. The navigational, structural and operational capabilities.
Aspect	Description of Aspect	Description of Aspect	Description of Aspect
Input	Not initially described	Not initially described	Not initially described
Output	Ice navigator has been assigned	A radar signal has been detected by ships radar	Aware of vessel's typical capability
Precondition	Not initially described	Not initially described	Not initially described
Resource	Not initially described	Not initially described	Not initially described
Control	Not initially described	Not initially described	Not initially described
Time	Not initially described	Not initially described	Not initially described
Name of function	Make shipping schedule		
Description	Expected departure and arrival times are determined.		
Aspect	Description of Aspect		
Input	Not initially described		
Output	Shipping schedule made		
Precondition	Not initially described		
Resource	Not initially described		
Control	Not initially described		
Time	Not initially described		

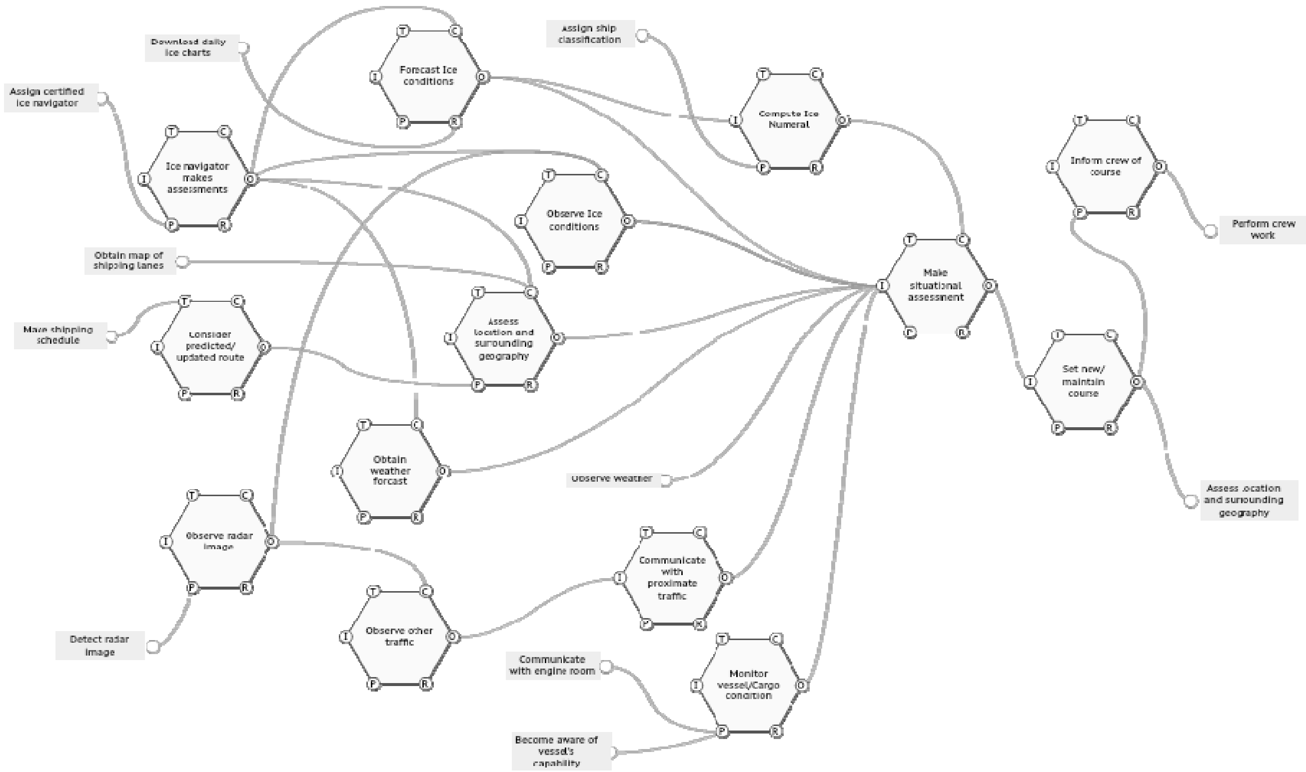

Figure 5. FRAM model for ship navigation with input from ship navigators

3.4 *Learning Variations*

Figure 5 shows a map of the potential ways that a ship could be navigated. But there are many ways the ship could be navigated, including combinations of the potential functional paths shown in Figure 5. This variability must be understood, if it is to be properly managed. Also, there will be more Arctic specific knowledge here, because Arctic ship navigation is a variation of ship navigation. See Table 2 for sources of variability and additional notes along with some ways this variability has been managed in the past. This model can help to better understand some shipping scenarios.

Table 2. Variability, notes and management strategies with focus on Arctic shipping

Associated Function	Sources of potential variability	Notes and Management techniques
Set new/ maintain course	More than one possible course	Slow down - allow time to receive more information – make more informed decision
	Scheduling and expected profits can influence decision making	
	The amount of consumable onboard also affect decision making (route selection)	
Assess location and surrounding geography	GPS may not be accurate at high latitude	
	Coastline and underwater mapping may be poor in areas of Arctic	
	Sounding could be inaccurate outside of shipping lanes	
Consider predicted/ updated route	Possible multiple routes - NWP has 3	Dynamic set of solutions
	Ice conditions may take you outside of shipping lanes	
	Search and rescue operation can take you outside of shipping lanes	
Compute Ice Numeral		This is computed once daily - when a new ice chart is published.
		The computation is based on the ice assessment from the ice chart - If the chart contains errors it will affect the appropriateness of the computation
Detect radar image	Small icebergs (growlers) can be difficult to detect in ice	Reduce speed - increase reaction time if detected late
	Small icebergs (growlers) can be difficult to detect in large sea states	
	Dome shaped icebergs may be problematic to detect	
	Sleet can affect performance of radar	
	Quality of the installed radar technology	
Observe Ice conditions	Darkness affects ability to see ice conditions	Good searchlight - very valuable and backup searchlights
	Experience of Ice navigator and Captain	With uncertain conditions, reduce speed to minimize force of unexpected impacts
	Real conditions can be worse than was forecasted	Deal with it and/or turn around
	Ice charts are published 24 hours - over 24 hours the ice will move	Try to use ice chart and radar to predict ships position in changing ice field. Also send helicopter for visual inspection if available. Important to remember that ice moves with wind and icebergs will move with current
Forecast Ice conditions	Quality of Ice chart	Quality usually improves if aerial assessment of the region has been done
	Forecast models may be poor for certain regions	Experienced ice navigator can also provide experience based forecasts
Obtain weather forecast	Forecast maybe poor quality or non-existent for some regions of the Arctic	Experienced ice navigator can also provide experience based weather forecasts of local weather patterns
	How many weather forecasts are available daily?	
	Communications problems at high latitudes can affect ability to obtain forecast	
Observe weather conditions	Can observe variety of conditions - Wind and snow can affect visibility - Cold rain can expect icing	
	Notice differences from weather forecasts	Ice navigator may be able to help determine how weather might change
Make situational assessment	Is full bridge team present?	Other work commitments may take them from bridge when assessment is made
	How much time to make assessment	Can slow down to make more time
	Here is the function that influenced by all other analysis functions	Variations of every upstream function will influence the quality of the assessment here
	Fatigue can affect assessments and decision making	Shift schedules can affect fatigue - Ice-induced vibrations can affect fatigue
	Ice pressure can be problematic for ship navigation, even in low ice thickness	
	Longer periods of darkness can affect decision making	
	Slush has the potential to clog cooling water intakes, and risk losing engine - this has been seen in the past	Finer screen over water intakes
	Icebreaker assistance may be called for if conditions become unmanageable for vessel.	When following/being towed by icebreaker: Keep prop turning, May have to follow very closely in

	This could take some time if not planned for in advance	high ice pressure field (channel will close in). Use ice to help stop when following closely (prevent collision)
Communicate with engine room	Communicate upcoming maintenance	Work culture may influence communication frequency
	Communicate performance issues	
Monitor vessel condition	Wet conditions or open water can promote marine icing	Breaking off the ice can also be a dangerous procedure and is usually avoided until absolutely necessary
	There are icing allowances in stability book	It is very difficult to monitor the weight of ice buildup and distribution of the weight
	Parallel mid-body stress will be high if entering a mobile ice field from fast ice (shear zone)	Avoid if possible
	Difficult to monitor (feel) bow impacts if bridge is positioned astern	
	Backing up in ice	Keep rudder straight when moving astern
Perform crew work	Crew may not be prepared for and have experience in cold climate	

4 DISCUSSION

It is important to understand that this model still has missing elements. It can be expanded to incorporate more elements to improve our understanding of socio-technical system that is ship navigation. It is acknowledged that there are regulatory functions and organizational functions omitted from this model. These functions are carried out at lower frequencies than the onboard functions, but will influence the onboard work. The next step is to better understand how these regulations and organization affect the functionality of ship navigation. It may be also appropriate to further define some functions. For example, it may be appropriate to break down the "Monitor vessel condition" function into separate functions, as in Figure 6.

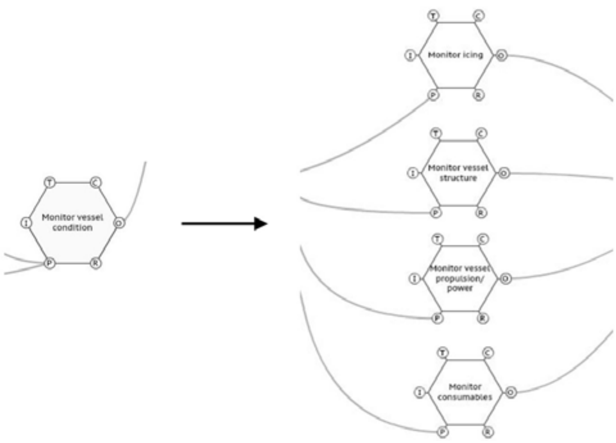

Figure 6. Breaking function into sub-functions

Then it may be appropriate to ask: 1) when is the FRAM model "complete"? and 2) How do we know if we have sufficient granularity? The model will never be complete but each revision should improve the understanding. There is no guarantee that future operations will mirror past operations, so there are always new lessons to learn. As long as the system is operating, there will be new information to add to your FRAM model. It will depend on what you are trying to explain and the explanations you are willing to accept. The detail of the function may be acceptable to explain one scenario, but inadequate to explain another. In this case, it is important to not try to categorize explanations into two discrete groups, right or wrong. Explanations can range from poor to acceptable, and further examination will produce better explanations. As more details are understood acceptable explanations will emerge. The question then becomes, what is acceptable? Explanations should be sought that not only describe what happened, but how it happened and why it happened. By understanding these 3 parts of a scenario, better management strategies will be able to be developed.

In order to demonstrate the utility of this information, it should be used to explain certain scenarios from the shipping domain. The FRAM model can be used to add to the understanding that have been obtained from traditional examination techniques. In section 4.1 the Exxon Valdez case will be considered.

4.1 *Applying a case: the Exxon Valdez grounding*

The Exxon Valdez grounded on March 24, 1989 on Bligh Reef in Prince William Sound while transporting crude oil from Valdez, Alaska to San Diego, California. This shipping accident is one of the most well-known, which garnered much media attention and legal intervention because of its environmental impact and ill-defined oil spill response policy. In terms of Arctic shipping accidents, the Exxon Valdez case is the most well documented accident that is publicly available. This case may be the most suitable case to examine through the lens of the FRAM because of the extent of information available compared to other cases.

All information in this case is taken from the National Transportation Safety Board's (NTSB) marine accident report on the Exxon Valdez accident (NTSB, 1990). The NTSB performed an extensive investigation and analysis of this accident. The report included 47 findings that were determined to be relevant to the accident, an account of probable cause, and recommendations to the organizations/departments involved. The report has been a very significant document for shipping safety and influenced the adoption of double hull tankships across the industry. The adoption of double hull tankships has improved safety of the tankship industry, specifically with respect to its relationship to the environment.

The account of probable cause is as follows (NTSB, 1990): *"The National Transportation Safety Board determines that the probable cause of the grounding of the EXXON VALDEZ was the failure of the third mate to properly maneuver the vessel because of fatigue and excessive workload; the failure of the master to provide a proper navigation watch because of impairment from alcohol; the failure of Exxon Shipping Company to provide a fit master and a rested and sufficient crew for the EXXON VALDEZ; the lack of an effective Vessel Traffic Service because of inadequate equipment and manning levels, inadequate personnel training, and deficient management oversight; and the lack of effective pilotage services."*

This account of probable cause can be visualized by the causal dependency diagram in Figure 7.

Figure 7. Causal dependency diagram produce from the account of probable cause given in the in the Marine Accident Report

Now consider how the grounding would look by applying the information in the grounding report to the FRAM model for Arctic ship navigation. The FRAM model shown in Section 3.3 displays the potential functional paths to navigating the vessel. The Exxon Valdez case can be used to illustrate the functional dynamics that contributed to the grounding. The generalized FRAM model seen in Figure 5 represents the potential ways that an Arctic ship navigator could operate the ship. However, when a ship navigator operates the vessel, many combinations of selected functions may be used. The marine accident report of the Exxon Valdez grounding can be used to help understand the functional dynamics that occurred during that accident (NTSB, 1990).

Figure 8 shows that at about 23h55 on March 23, 1989 the Navigator (Third Mate) and his team were assessing the location of the Exxon Valdez relative to Busby Island Light to determine if it was time to turn back towards the shipping lane that they had left to avoid glacial ice. At this time, the navigator was using the radar to estimate the vessel's position from Busby Island Light, which he estimated to be 0.9 miles away. Also, a fix was plotted on a chart of the vessel's position from visual observations, which estimated Busby Island Light to be 1.1 miles away. There was a discrepancy of 0.2 miles of the navigator's estimates of the vessel's position. Additionally, during this functional snapshot there was an additional functional relationship learned that existed between observing the radar image and assessing the vessel's location and surrounding geography. This relationship was not noticed in previous discussions with ship captains and was added to the model (one of the blue lines in Figure 8) to add to the model's comprehensiveness.

In this analysis, the functional signature of the Exxon Valdez was presented. This represents a single voyage for this vessel. From this data alone, it is difficult to determine with high certainty what caused this accident. However, if there was data available about other voyages that the Exxon Valdez had and successfully navigated through Valdez Narrows, there would be a better understanding of the functional signatures that promoted better performance of the Exxon Valdez. Presumably, the vessel successfully navigated the Narrows before while the captain was away from the bridge, while workers were fatigued, or while glacial ice entered into the shipping lanes. By using a method that is capable of also analyzing successful voyages, there is a better chance of identifying what was different about the functional signatures that promote such different outcomes. Additionally, if this information was available, the value of this analysis could be increased.

By considering systemic safety solutions and understanding the navigational processes, additional safety recommendation can be made. For instance, in addition to recommending minimizing fatigue by analyzing ideal shift schedules, elements could be introduced into the system that help navigators perform better even when fatigued. It can be reasoned that even under ideal sleeping conditions, e.g. a person working a 9-5 desk job, a person can arrive at work tired or fatigued. Additional recommendations of updating the autopilot system to be more evident as to when it was engaged or disengaged, as this was a source of confusion for the crew of the Exxon Valdez during the grounding. This could help fatigued workers be more aware of the condition of their vessel. Additionally, other technologies could be recommended that help ship navigators more accurately assess their location in a waterway. In the present, the addition of GPS on vessels may help with this although, some of the Captains used in section 3.3 have expressed concern about GPS accuracy at high latitudes.

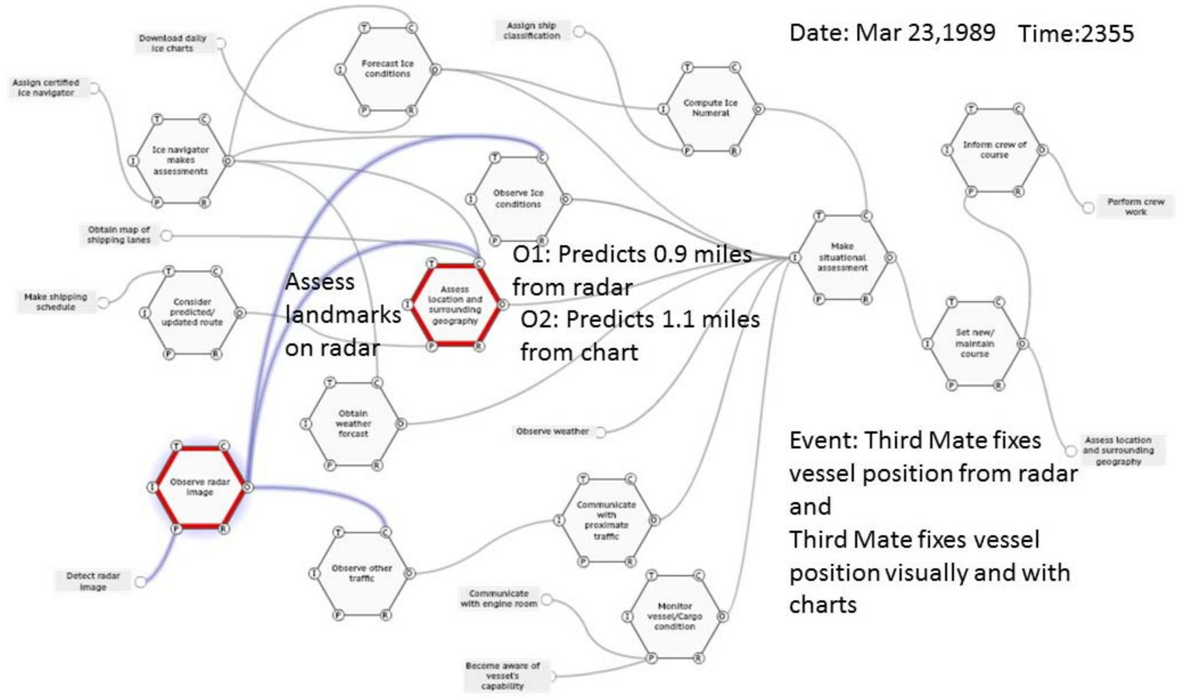

Figure 8. Functional representation of the Exxon Valdez grounding at about 23h55 with updated functional relationship (blue lines)

5 CONCLUSIONS

In this work, the FRAM has been used to start an investigation into Arctic shipping by trying to understand ship navigation and its variations in ice. The process of building a FRAM model was discussed and an application of the model was illustrated using the Exxon Valdez grounding. After speaking with the ship navigators, a more detailed FRAM representation of ship navigation has been developed. Some of the variations and conditions that are present in Arctic navigation are discussed along with the ways that ship navigators manage these conditions. The grounding of the Exxon Valdez was examined and provided context to the information that was made available by the Marine accident report. This case allowed for an alternative perspective and complementary discussion of the case than could have been had without the FRAM.

It is acknowledged in this work that there are still elements that factor into the ship navigation process that are omitted for now, including many regulatory functions and organizational functions. This work serves as an initial starting point to use the FRAM to help better understand the complexities that exist for ship navigation in the Arctic. This work can be improved in the future by further defining the functional descriptions, incorporating more variations that have been experienced, and extending the scope of the assessment. The framework to do this is presented in this paper and new information can be used to update the model.

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