Case Study

Mental Models of Navigation Safety to Inform Risk Management Decisions: Case Study on the Houston Ship Channel

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Abstract: The Houston Ship Channel (HSC) is one of the busiest waterway corridors in the United States. Since the channel's expansion in 2005, concerns have arisen about design deficiencies in the HSC in the area of the Bayport Ship Channel (BSC), especially north of the turn at Five Mile Cut. A mental models expert elicitation exercise was conducted in order to identify safety concerns arising from these design deficiencies and provide qualitative data that can structure analysis of technical data like those from automatic identification system (AIS) databases, which can better connect possible design deficiencies to incident outcomes. The elicitation produced an influence diagram to enable later causal reasoning and Bayesian analysis for the HSC and BSC confluence and nearby areas on the HSC, and helped to prime a comprehensive study of the feasibility of safety and performance modifications on this reach of the HSC. **DOI: 10.1061/AJRUA6.0000963.**

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Introduction

The U.S. Army Corps of Engineers (USACE) will spend roughly $1.95 billion in fiscal year 2016 on the nation's inland and coastal navigation infrastructure, comprising over 40,250 km (25,000 mi) of navigable channels responsible for handling 2.09 billion metric tons of commerce annually (USACE 2015). However, large-scale engineering decisions related to the safe construction, operation, and maintenance of these channels hinge upon information that may be derived from several disparate sources, including engineering studies, modeling and forecasting, and expert judgment (Kiker et al. 2005). Moreover, decision makers must contend with multiple lines of information that contain uncertainties regarding magnitudes, probabilities, and frequencies (Linkov et al. 2013, 2014; Suter and Cormier 2011; Bates et al. 2016), as well as multiple, sometimes conflicting, stakeholder groups (McDaniels et al. 1999; Collier et al. 2014; Linkov et al. 2012). In large organizations such as USACE and many other federal government agencies, the coordination and management of knowledge across different individuals in different functional groups with different specializations is especially important (Linkov et al. 2012; Trump et al. 2015). Organizational knowledge may be distributed across many individuals at varying levels of explicitness (Gough 2007). Understanding the users and generators of that information, as well as the interdependencies between physical, engineering, and business processes, is critical for effective management of institutional knowledge (Simonse et al. 2015; Rao et al. 2012). Moreover, the effective appraisal and use of that knowledge in decision making is critical to directing action toward achieving organizational goals.

Decision makers in the USACE and similar organizations use multiple and disparate information sources to make evidence-based, navigation-related decisions that account for risks, costs, and benefits (Blaunstein et al. 2014). One approach to capture a diverse set of perspectives regarding complex sociotechnical problems is mental modeling (Morgan 2002; Wood et al. 2012, 2017b), a qualitative research approach used to understand deeply held networks of knowledge, beliefs, and opinions held by individuals related to a topic of interest. This qualitative research approach is often used to capture the current state of knowledge related to scientific or engineering processes. The information in this mental model is represented as a directed network where concepts are represented as nodes and those concepts at the tail of an arrow produce an influence on the concept at the arrow's head. Once current state knowledge is captured through expert elicitation or stakeholder interviews, these diagrams facilitate comparison to knowledge of laypersons who need to be educated about risks associated with these processes via a risk communication plan (Bostrom 2008; Bostrom et al. 2013), for identifying opportunities to improve these processes (Collier et al. 2016; Wood et al. 2017a), or for developing decision support tools that help individuals navigate complex scientific, technical, or regulatory environments (Bridges et al. 2012; Kovacs et al. 2017).

Mental modeling methods have been used in a variety of settings (Wood et al. 2017b). Related to the field of transportation, mental modeling was used in evaluating the feasibility of implementing an automated highway system (AHS) for the state of California (Hall and Tsao 1997; Fossati et al. 2011). AHS experts provided information through structured interviews to determine what they

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believed to be the most significant risk toward deploying such a system, and researchers supplemented those interviews with the findings from a series of follow-up meetings with the Partners for Advanced Transit and Highways (PATH), California Department of Transportation (Caltrans), and Lawrence Livermore National Laboratory in an attempt to both assess the potential risks the AHS involved as well as to identify solutions toward resolving those issues. Interview and follow-up meeting results were then integrated into an influence diagram illustrating the relationships between factors that might dictate the feasibility of an AHS.

Influence diagrams have also been used to reduce the risks associated with oil transportation in the Gulf of Finland (Lehikoinen et al. 2012). Data here were collected from a questionnaire of 96 Finish maritime experts. These individuals reported their backgrounds and views on the effectiveness of safety regulations and practices as well as the need for further regulation and the effectiveness of safety inspections in reducing the likelihood of oil spills (Kuronen and Tapaninen 2010). From these results, Lehikoninen et al. (2012) were able to develop an influence diagram, which was geospatially integrated with ecological data to create a tool predicting the risk involved given the occurrence of an oil spill in various locations with differing amounts and types of oil and the likelihood of such a spill occurring.

Dombroski et al. (2006) used a similar technique to better develop policies and protocols for evacuation situations that anticipate and enhance evacuation compliance rates. They first developed an influence diagram showing the relationships between variables and used the results of interviews with 15 experts on the matter to estimate compliance in six different scenarios. A second set of interviews responded to by 32 emergency coordinators focused on the estimated results on compliance of four compliance initiatives. The results of the expert opinions of the level of compliance in these hypothetical emergency scenarios were similar to the level of compliance seen in recent emergency situations such as Hurricane Katrina.

Selecting navigation safety alternatives is a multistakeholder process with distributed knowledge, uncertainties, and constrained resources. Decision makers require methods by which to gather and assess quantitative and qualitative knowledge in a systematic and transparent manner (Menzie et al. 1996; Linkov et al. 2011; Suter and Cormier 2011). This paper presents a mental modeling exercise to gather expert knowledge, represent the problem space, and inform risk management decisions based on a case study conducted at the Houston Ship Channel (HSC), Texas, United States.

Methods

Study Area

The case study area is centered along the HSC, at and around the location of the intersection with the Bayport Ship Channel (BSC; Fig. 1).

The HSC is 162 m (530 ft) wide and 14 m (45 ft) deep in that area, with 72-m (235-ft)-wide, 4-m (12-ft)-deep barge lanes on either side of the main channel (NTSB 2012). The BSC terminates at the Bayport Terminal, with a 11-m (37-ft) depth and a width of 91 m (300 ft) (Davis and Webb 2012). The BSC widens to a flare with a radius of 914 m (3,000 ft) at the intersection with HSC. As vessels travel northbound along the HSC, they must negotiate a slight starboard bend just south of the Bayport Flare and continue traveling north along the HSC or make a sharp port turn to enter the BSC. Vessels entering the BSC usually require tug assist (Davis and Webb 2012).

The HSC is a particularly busy channel, with monthly transits ranging from 11,706 to 14,533 in 2014, and between 1999 and 2014, traffic increased 10.93% (Nerheim 2015). The unique channel configuration in the area of the Bayport Flare, along with trends suggesting an increase in vessel traffic and vessels of larger size, increases the likelihood for incidents such as collisions, allision, and groundings. As such, the area around the Bayport Flare was listed by the U.S. Coast Guard as a "precautionary area" (NTSB 2012).

Collisions in the HSC can potentially carry high consequences. A collision in 2011 between the tank ship *Elka Apollon* and the container ship *MSC Nederland* resulted in damage to those vessels of $1.5 and $1.3 million, respectively (NTSB 2012). More recently, a chemical release from the collision of the *Carla Maersk* and the *Conti Peridot* on March 9, 2015, resulted in a 24-h shelter-in-place order for Morgan's Point, and the Port of Houston was closed for more than three days (Glenn 2015). Given the area's chemical and petroleum industries, collisions and other incidents carry the potential for the loss of hazardous chemical cargo, which may result in environmental degradation and economic losses.

Investigative Methods

Expert Elicitation

A mental model expert elicitation (Morgan 2002; Wood et al. 2012, 2017a) was conducted in order to better understand the important variables and causal pathways that lead to undesired outcomes (e.g., vessel groundings, near misses when meeting) when navigating the HSC in the area of the BSC. A Draft Expert Model was developed by reviewing authorization and channel design guidance documents (USACE 1984, 1995, 2008, 2015) and consulting with project sponsors. This draft model identified several categories of concern (e.g., abilities required for a vessel to successfully navigate the HSC), specific examples of each category (e.g., steerage), and the relationship between categories (Fig. 2). This information is represented as an influence diagram, where nodes represent concepts of interest and arrows represent the direction of influence between concepts. For example, in the Fig. 2, Incidents are the specific scenarios of concern that, should they develop, result in harmful Consequences for the HSC and the individuals who work and live near it. If an Expert Model influence diagram complies with certain rules based in Bayesian logic (e.g., Howard and Matheson 2005), the influence diagram can be transformed into a decision tree and paired with available data to model the effect of changes in upstream nodes on downstream nodes, enable actionable decision making, and facilitate analyses to understand the value or importance of specific pieces of information in enabling a decision maker to reach a conclusion.

The information identified in the Draft Expert Model was used to develop and execute structured interviews with 13 subject matter experts (SMEs) from different stakeholder agencies to better understand the relationship between categories and the interdependencies between examples across category boundaries. Stakeholder agencies were split between U.S. Army Corps of Engineers groups (Galveston District, Southwestern Division, Institute for Water Resources, Engineer Research and Development Center), groups that use or manage traffic on the HSC (Houston Pilots Association, Port of Houston Authority), and consultants who had done work in support of the HSC and its tributary channels (WES Consulting, Gahagan and Bryant Associates). Results of these interviews were reviewed to develop a Final Expert Model that described the relationships between exemplars using the same influence diagram approach as that used for the Draft Expert Model.

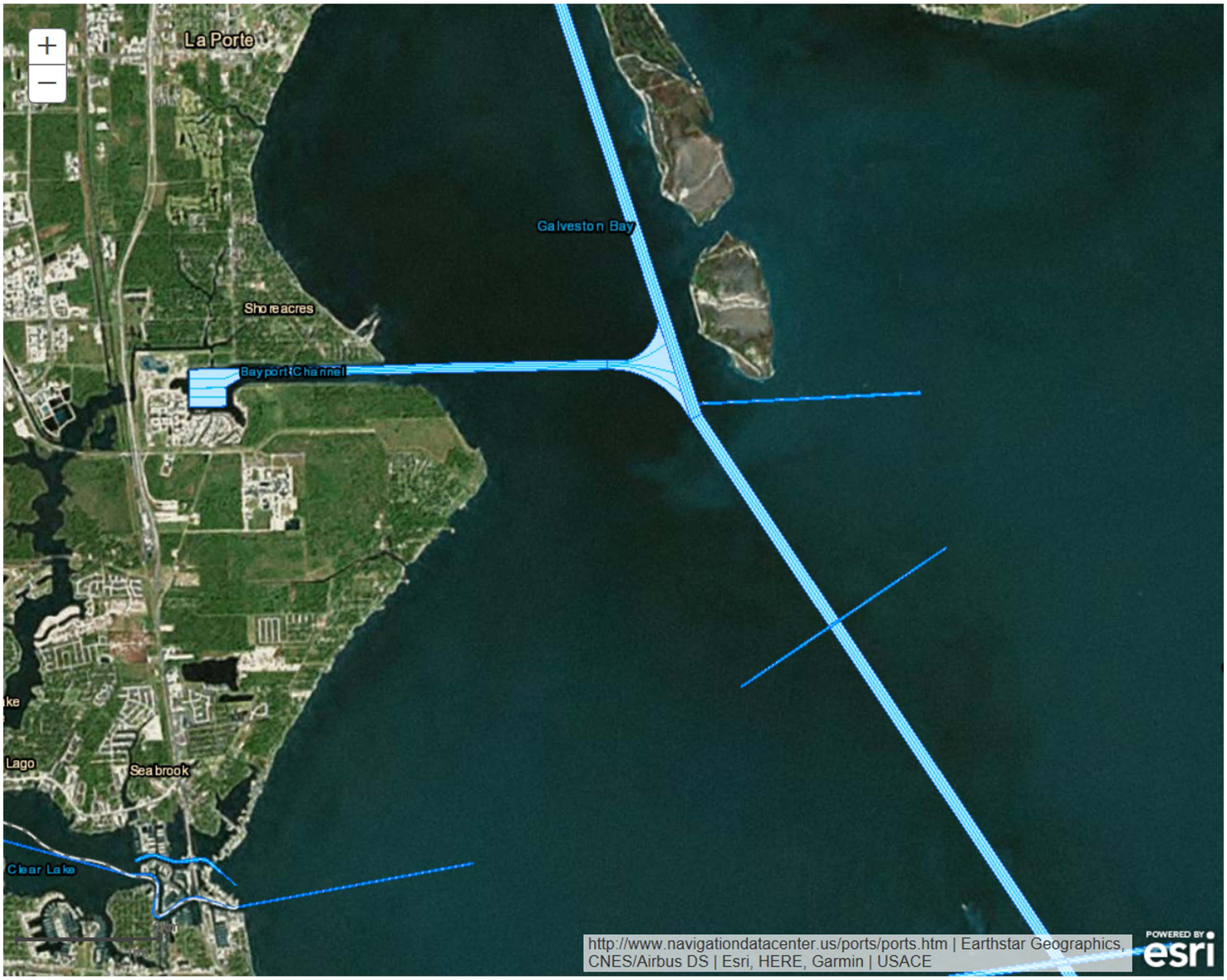

Fig. 1. Bayport Ship Channel (BSC) with approach flare showing connection to Houston Ship Channel (HSC) (map data © ESRI, Earthstar Geographics, CNES/Airbus DS, Esri, HERE, Garmin, USACE, http://navigationdatacenter.us/ports/ports.htm)

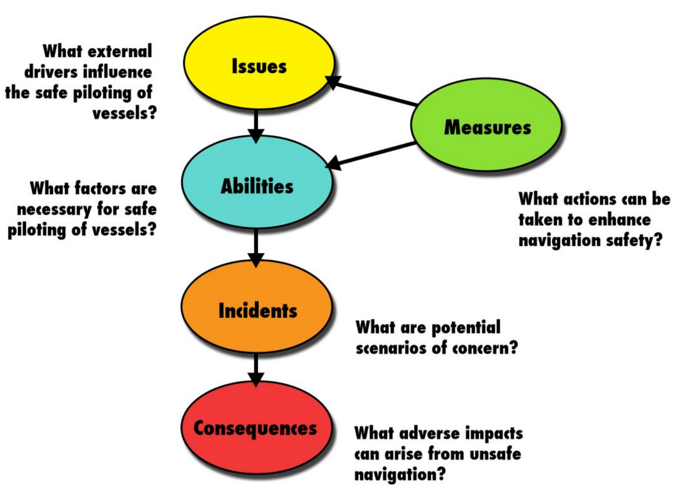

Fig. 2. Draft expert model of HSC navigation

The Final Expert Model was validated via webinar with four additional SMEs in the engineering and science of channel design and related issues with some experience with the HSC or similar projects in the Gulf region. These experts asked several questions of clarification during the course of the webinar, but did not have any fundamental objections to the model's organization.

Confirming Expert Knowledge via AIS Data

Automatic identification system (AIS) technology has developed in recent decades primarily as a means to improve marine safety and maritime domain awareness (Tetreault 2005). AIS uses the very high frequency (VHF) radio spectrum to broadcast and receive (ship-to-ship, ship-to-shore, and shore-to-ship) real-time information concerning vessel identities, dimensions, positions, speeds, and headings, among other fields (U.S. Coast Guard National Data Center 2015). At present, the AIS data standard supports 27 message types, as described by the latest International Telecommunications Union recommendation document ITU-R M.1371-5 (ITU 2014). In the United States, 33 CFR §164 mandates carriage requirements for commercial vessels and assigns enforcement duties for equipment carriage, message formatting, and data archiving to the U.S. Coast Guard.

Though intended primarily as a collision avoidance and port security system, AIS technology also provides a data-rich capability for quantifying the complex and dynamic interactions between commercial shipping vessels and maintained navigation infrastructure (dredged channels, coastal structures, etc.), the natural marine environment, and broader global and national freight flows and economic activity. Scully and Mitchell (2015) noted that AIS technology can be used for monitoring channel alignment, vessel performance, and accident investigations. There have been many studies in recent years using archival AIS position reports to measure or estimate environmental impacts of shipping, such as air emissions (Pitana et al. 2010; Perez et al. 2009), underwater noise levels (Hatch et al. 2008), and whale strikes (Wiley et al. 2011). Mitchell and Scully (2014) presented an AIS-based methodology for quantifying the degree to which deep-draft vessels are dependent on tidal elevations when transiting coastal entrance channels, and also introduce a basis for tracking inland waterway travel time statistics via AIS data. Dobbins and Langsdon (2012) demonstrated the use of AIS records to generate origin-destination vessel movements for freight flow tracking along inland waterways. In Europe, Bayesian belief networks, AIS data, and expert elicitation have been combined to assess grounding risk (Hanninen et al. 2013; Mazaheri et al. 2015), oil spill risk from tanker collision and associated cleanup costs (Montewka et al. 2013; Goerlandt and Montewka 2015; Valdez Banda et al. 2016), and open sea collision risk for passenger ferries (Montewka et al. 2014), and to develop holistic formal safety assessment frameworks for the Gulf of Finland (Haapasaari et al. 2015).

In this study, a full year (2013) of AIS position reports sampled from the Galveston entrance channel was used to analyze aggregated statistics of navigable waterway performance in terms of how efficiently deep-draft vessels transit the study area where the BSC branches off the HSC. Although vessels underway typically broadcast via AIS every 6 s (ITU 2014), to keep data file sizes and processing times manageable for this study, position reports containing lat and lon, speed, heading, and course over ground were sampled at 5-min intervals. Data were plotted in GIS to create a heat map.

Results

Draft Expert Model

The Draft Expert Model consists of five nodes, each of which corresponds to a causal variable that should be considered when trying to change the rate of incidents in the HSC and the resulting consequences. The model starts with *Measures*, or the actions that can be taken to enhance navigation safety. These actions can be taken by USACE, by another stakeholder, or through partnerships between USACE or stakeholders. For example, USACE might partner with the Port of Houston Authority and the Coast Guard to deploy additional aids to navigation (AtoNs) on the HSC that improve visibility for ship pilots maneuvering within the S-turn south of the Bayport flare.

Measures influence *Issues*, the external variables that affect the safe piloting of vessels in the HSC. Issues and measures both influence *Abilities*, the factors that are necessary for the safe passage of vessels. Returning to the example, AtoNs are a measure that enhances the ability of pilots to see channel features and may help to attenuate visibility issues caused by fog. If *Abilities* do not attenuate an *Issue*, they can lead to an *Incident*, such as an allision if the edge of the channel is not detected in time. *Incidents* in turn lead to *Consequences*. If a container ship is involved in an allision because it could not detect an AtoN in time as a result of fog and a container falls off the deck and into the water as a result, the consequences could include negative outcomes to the oyster beds and wildlife nearby from product spillage, physical injury from the force of running into a fixed object, damage to the ship, and so on.

Simple Expert Model

The Simple Expert Model (Fig. 3) was developed based on initial impressions of common themes from SME interviews. Nodes are organized by where they best align to the concepts in the Draft Expert Model. Tiers are structured in the Simple Expert Model similarly to in the Draft Expert Model, where tiers at the top of the model tend to influence tiers at lower levels. At the top are specific *Measures* that were most mentioned in the structured interviews, which included various widening or deepening projects for both channels, improved AtoNs, and changes to administrative rules. Bend easing and flaring was the highest-cited measure, referenced by nearly all SMEs.

Issues fell into three primary categories. The first of these is *Traffic Management*, in particular congestion caused by the increased size and volume of vessels entering the HSC. *Channel Configuration* issues are those that make navigation difficult when transferring between the HSC to the BSC and vice versa or accommodating traffic transferring between these channels while traveling south on the HSC. Finally, *Environmental* issues are those that threaten the health of flora and fauna as a result of shipping activity, like threats to oyster beds and other wildlife from release of product, and air pollution caused by ships idling at the mouth of the channel waiting for congestion to clear.

A broad collection of *Abilities*, which enable effective navigation in the face of *Issues*, were identified. These include maintaining a *Speed* that is fast enough to facilitate *Maneuverability* (agility of steerage and ability to maintain it) but not so fast as to lose control. *Comms/Data* support development of a common operating picture across pilots about the location, size, and movement of vessels in the channel as well as current channel conditions, and facilitate ships to cross and successfully pass each other in the HSC. *Movement Affordance* refers to the interaction of channel features (e.g., depth, width, turns) and ship features (e.g., breadth, draft) that create space for ships to navigate in the channel.

Several *Incidents* were noted, which occur when *Abilities* are unable to overcome potential *Issues*. Though *Near Misses* and *Collisions* between ships were cited as a significant safety concern, *Allisions* between a ship and fixed object (e.g., AtoN, bridge pylon) and *Groundings* were also provided as incidents of interest. Many of these incidents can exacerbate or even create *Congestions/Closures* of the channel that are becoming increasingly common from normal traffic volumes.

Consequences that result from *Incidents* fell into three broad categories. *Environmental* consequences are impacts to flora and fauna from sources such as lost ship cargo or increased air pollution from idling in or near the channel during congested periods. *Health & Safety* consequences are the human health concerns faced either by pilots and crews onboard a ship experiencing an incident, or by residents and bystanders in the area who may become involved in the incident, experience impacts from a loss of hazardous material, and so on. *Economic* consequences include losses to the regional economy from port and channel closures, to the shipping companies and manufacturers from lost product, and to local residents and property owners from damage to their land or facilities.

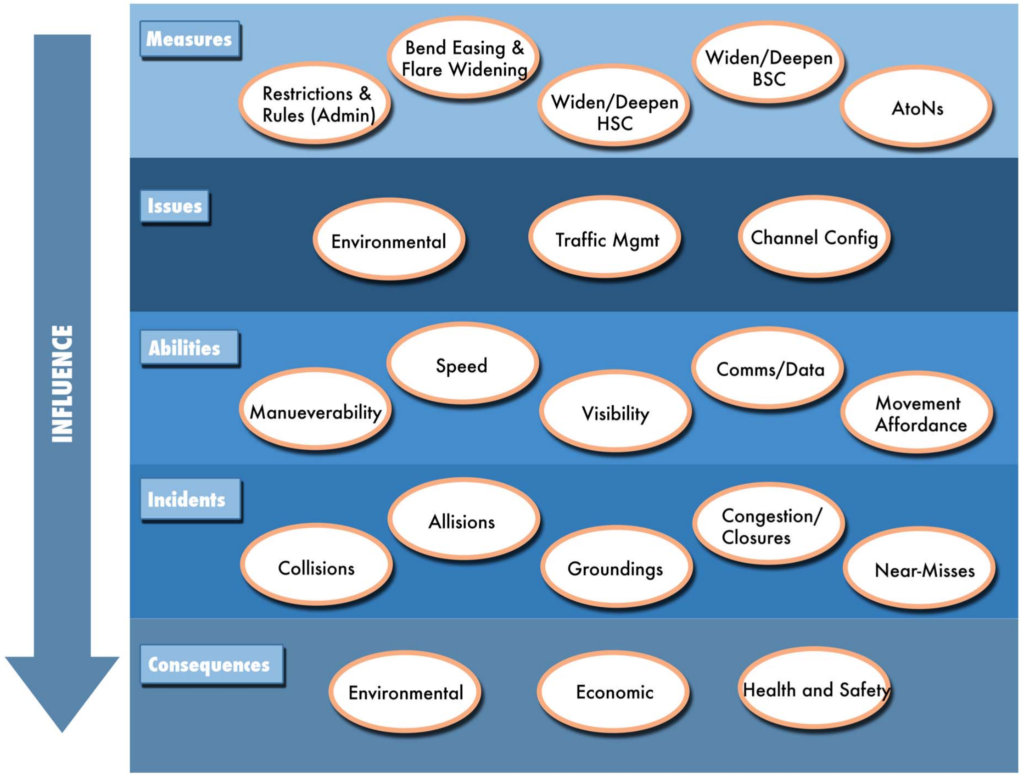

Fig. 3. Simple expert model of HSC navigation; topics are identified by SMEs, grouped by category

Detailed Expert Model

Interviews were reviewed to develop an influence diagram outlining the relationships between concepts identified in the Simple Expert Model, identify additional concepts that were not captured in the Simple Model, and better understand clustering between related concepts and their effects on other concepts in the model. A detailed description of the concepts in the resulting Detailed Expert Model (Fig. 4) can be found in Table 1.

Measures were found to cluster into *Channel Modifications*, *Pilot Preparedness*, and *Tug Use*. *Channel Modification* includes any changes to physical features of either the HSC, BSC, or their confluence. The most commonly cited measure in this category was by far *Bend Easing & Flare Widening*, the exact specifications of which have been the subject of extensive simulation studies (Davis and Webb 2012; Waterway Simulation Technology 2011). Measures in the area of *Pilot Preparedness* include *Pilot Simulation Training* to provide pilots with practice navigating conditions like those in the HSC using a safe environment, and *Admin Rules & Restrictions* that set rest periods, minimum staffing requirements, and other rules to assure that pilots are alert and have all the tools available at their disposal to perform their job effectively. *Tug Use* became a prominent theme on closer inspection of the data; several proposed measures fell into this cluster. The most highly cited of these was to *Increase # of Tugs* because wait times for tug assists in the HSC can currently be up to several hours. In addition, measures to reduce congestion resulting from tug traffic were proposed, including *Add Tug Feeder Channel* to keep tugs out of the main channel until the time they are needed, and *Improve Tug & Barge Information Systems* to increase pilots' awareness of tugs and other craft on the HSC and facilitate coordination.

The *Issues* identified in the SME interviews clustered into *Traffic Management*, *Channel Configuration*, and *Environmental Issues*. *Traffic Management* issues included the number of craft in the channel (*Number of Ships, Number of Tugs*), their size (*Length/Beam of Ships*), and their wind fetch (*Wind Fetch of Ships*). These all influence the amount of space available in the channel for pilots to navigate ships. Wind fetch requires pilots to crab when winds are high and causes ships to take up additional width in the channel. Length and beam of a ship have a similar effect because longer or beamier ships need more channel width to execute turns. The cluster of *Environmental Issues* includes concerns that change the ability to navigate in the HSC, including *Current*, *Fog*, *Wind*, and *Storms*. The *Channel Configuration* cluster is composed of channel features that are important to the safe navigation of the HSC. These include *Turning Areas* that allow ships to successfully turn into and out of tributary channels, *Outlets/Docking* that provide opportunities for disabled ships to move out of the main channel and alleviate congestion, *Shoaling* that limits the area available in the channel for craft to navigate within, and *Bank Effects* and *Hydraulics & Hydrodynamics* caused by the interaction of water movement with channel banks and craft hulls that can either enable (e.g., Texas chicken; Arnsdorf and Murtaugh 2014) or confound the safe navigation of the HSC.

The number of *Abilities* that SMEs cited that were important to safe navigation in the channel were limited and referenced as distinct from one another, with the possible exception of *Data & Information Systems* and *Communication* capabilities, which enable pilots to develop a common operating picture and coordinate action across craft. Indeed, these were clustered as one node in the Simple Expert Model, but were broken into separate nodes for the Detailed Expert Model because the technology systems that support each are distinct.

The number of *Incidents* cited by SMEs was similarly limited and did not expand beyond the Simple Expert Model. In the Detailed Expert Model, the links between *Near Misses* and *Consequences* are represented as dashed arrows because these incidents

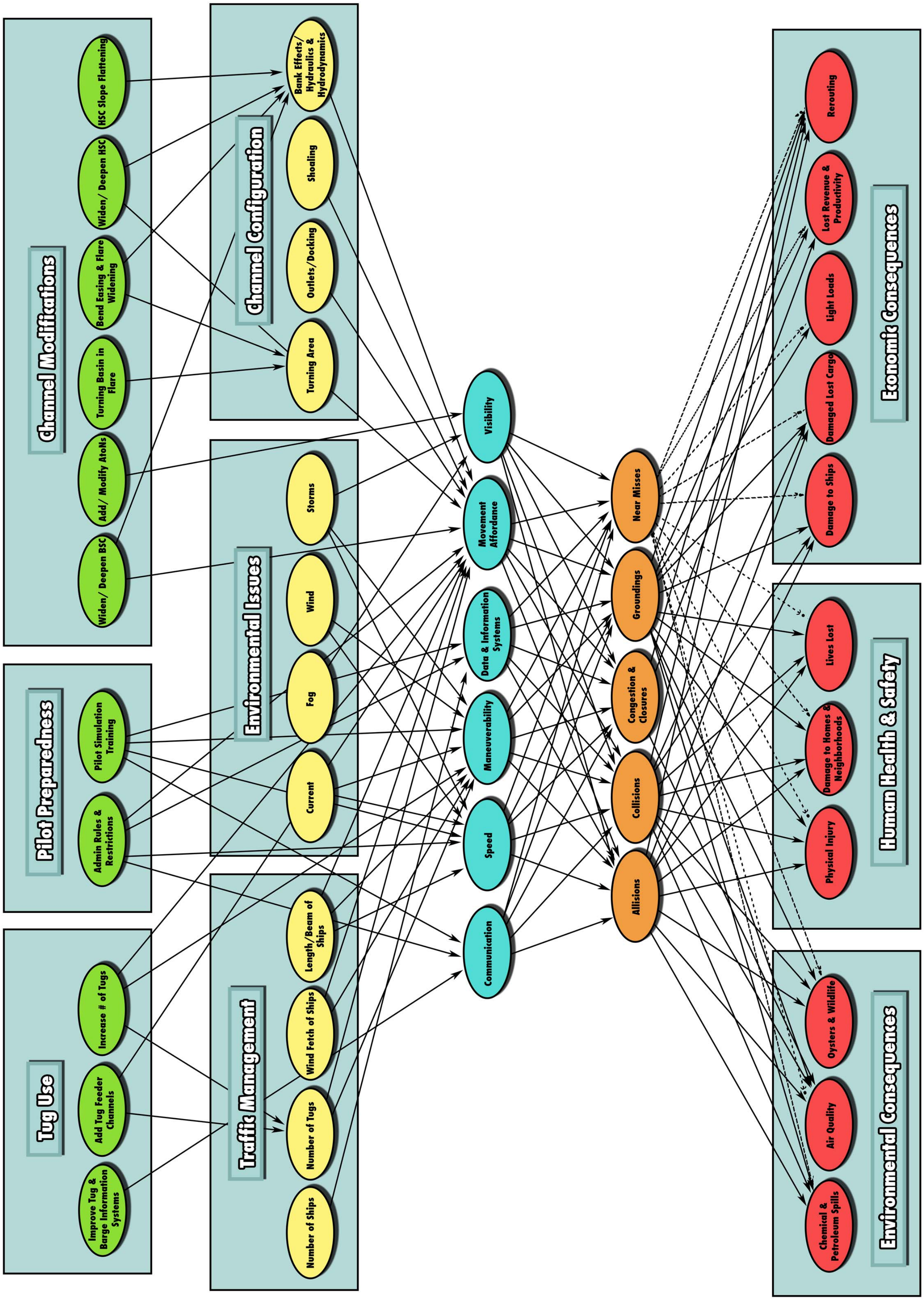

Fig. 4. Detailed expert model of HSC navigation

Table 1. Description of Detailed Expert Model Concepts

Category	Concept	Description
Measures		
Tug use	Improve tug and barge information systems	There is currently no requirement for tugs and barges to be equipped with AIS, and other communication equipment may be quite rudimentary on these craft. This measure would enhance AIS or communication capabilities.
	Add tug feeder channels	Proposed measure to add channels deep enough for tugs to navigate but that are far enough outside of the main channel that tugs do not get in the way of ships that they are trying to assist or other vessels in the channel.
	Increase number of tugs	Ships that encounter trouble in the HSC may wait a long time before a tug becomes available to assist. This proposed measure increases the number of tugs, thereby increasing the availability of tug assist.
Pilot preparedness	Admin rules and restrictions	These are proposed or current measures to reduce congestion or potential safety concerns in the channel through setting staffing requirements, rest cycles, and procedures for channel navigation.
	Pilot simulation training	Proposed measure to increase pilot simulation training, in part to give pilots more practice navigating in a safe environment and in part to develop data or that may be used to improve channel design or to prototype proposed designs.
Channel modifications	Widen/deepen BSC	Proposed measures to widen and/or deepen some or all of the BSC.
	Add/modify AtoNs	Proposed measures to add aids to navigation or modify existing aids to make them more effective.
	Turning basin in flare	Proposed measure to create a turning basin in/near the confluence of the Houston and Bayport Channels that would require tug assist for ships to enter/exit the BSC from the HSC.
	Bend easing and flare widening	Proposed measure that would ease the bend in the S-curve south of the BSC flare and widen the flare to reduce the shift in momentum and turning angle required to navigate both features.
	Widen/deepen HSC	Proposed measure to widen and/or deepen the HSC.
	HSC slope flattening	Proposed measure to reduce the slope angle of the east bank of the HSC in the area of the flare to reduce hypothesized bank effects that make steerage unstable when navigating into the HSC/BSC confluence.
Issues		
Traffic management	Number of ships	The number of ships entering both HSC and BSC is increasing, resulting in increased congestion and coordination challenges.
	Number of tugs	The number of tugs available to assist a ship in the HSC often outstrips the demand for tugs in the channel.
	Wind fetch of ships	Larger ships, e.g., automobile carriers and large container ships, have a large surface area on their broadside which increases the extent to which their steerage is influenced by wind.
	Length/beam of ships	The length and beam (width) of ships affects their ability to maneuver in the channel, and to cross other ships navigating the channel.
Environmental issues	Current	Currents are relatively stable in both channels, though cross-currents in the BSC may require pilots to steer ships into the current (a technique called *crabbing*) to successfully navigate the channel. This increases the width of the channel required for the ship to navigate beyond its beam width.
	Fog	Fog reduces visibility in the channel and can make navigation more difficult.
	Wind	Wind effects have consequences similar to those for current, requiring ships with high wind fetch to steer into the wind slightly in order to successfully navigate the channel. This increases the width of the channel required for the ship to navigate beyond its beam width.
	Storms	Storms can increase the intensity and variability of winds and currents, and can also reduce visibility as a result of fog or rain.
Channel configuration	Turning area	The area in the HSC and tributary channels that allow for ships to turn into and out of tributary channels successfully.
	Outlets/docking	Docks and outlets are areas where ships may stand while waiting for congestion to clear or for tug assist.
	Shoaling	Normal sedimentation that builds up over time along the floor and/or banks of a navigation channel. Severe shoaling may reduce the maximum safe draft or beam of ships entering/exiting the navigation channel.
	Bank effects/hydraulics and hydrodynamics	Suction or repulsion effects caused by the interaction of a ship's hull with the banks or floor of the shipping channel. These can serve as an aid when crossing other ships (e.g., hydrodynamic pressure prevents ships from colliding when performing the "Texas chicken"), or as a challenge when crossing into areas of the channel with drastic changes in configuration (e.g., depth of the HSC/BSC confluence is much deeper than the HSC or BSC alone).

Table 1. (*Continued.*)

Category	Concept	Description
Abilities		
—	Communication	The ability to communicate with other craft in the channel. This includes AIS map serves that provide the location, speed, and heading of ships, as well as radio or other communication technologies that allow ships, barges, tugs, and other craft to coordinate their actions.
	Speed	The ability to maintain an acceptable range of speed in the channel. A minimum speed is required to enable ship steerage. Ships that navigate the channel too quickly may not be able to turn in time.
	Maneuverability	The ability to turn and otherwise navigate a channel. Thrusters placed at the bow in addition to the stern can enable maneuverability by making it easier to initiate or maintain a turn.
	Data and information systems	The ability to use current information about channel, weather, and traffic conditions. Some of these data streams are embedded in information systems (e.g., AIS) that serve both an information function and a communication/coordination function.
	Movement affordance	The space required to move a ship with particular draft/length/beam through the channel.
	Visibility	The ability to see other ships, structures, and natural features above the water's surface in and near the channel.
Incidents		
—	Allisions	Contact of a ship with an AtoN, structure, or other fixed manmade object.
	Collisions	Contact of a ship with another ship, barge, tug, or other craft.
	Congestion and closure	Traffic effects caused by an increase in channel use or another incident in the channel.
	Groundings	Contact of a ship with the channel bank or floor, or natural bank or floor.
	Near misses	Potential incidents (especially allisions and collisions) which ultimately did not occur.
Consequences		
Environmental Consequences	Chemical and petroleum spills	Loss of petroleum, chemicals, or other liquid products often transported by a tanker craft as well as the environmental repercussions associated with that loss of product.
	Air quality	Degradation of air quality as a result of a loss of product (e.g., chemical spill) or exhaust from idling ships or land transport.
	Oysters and wildlife	Impacts to oysters and other wildlife that are plentiful in Galveston Bay and areas in the vicinity of the HSC.
Human health and safety	Physical injury	Those injuries to persons resulting to crew or bystanders from the force of running into a fixed object, damage to the ship, etc.
	Damage to homes and neighborhoods	Harm to property including or surrounding a domicile(s) and the neighborhoods in which they are situated. This may include physical damage from collision by ships or objects, fouling of wells or other potable water delivery, or other sorts of damages.
	Lives lost	Loss of life caused directly from an incident, or indirectly from the near-term effects associated with another consequence.
Economic consequences	Damage to ships	Damage to the physical structure of the ship or its ability to operate as a result of an incident.
	Damaged/lost cargo	Damage or loss of solid or liquid cargo as a result of an incident.
	Light loads	Need to load a ship at a weight or volume lower than its capacity in order to be able to draft at an acceptable shallow depth to navigate the channel. Results in increased cost to handle a smaller amount of freight.
	Lost revenue and productivity	Losses of income or ability to work on the part of shipping companies, manufacturers, and the Port of Houston as a result of stoppages, congestion, or other incidents that reduce the ability to navigate the channel and move goods successfully.
	Rerouting	Loss of work and regional economic benefit as a result of changes to ship routing that may result near term from stoppage caused by a specific incident, or long term from the threat of incident.

themselves could result in *Consequences* only if something occurred during the event that changed the outcome to one of the other *Incident* concepts.

A large number of *Consequences* were cited, especially those related to one craft striking another craft or some object. *Consequences* clustered into *Environmental Consequences*, which are harmful outcomes for the environment, e.g., those caused by *Chemical & Petroleum Spills*; *Human Health & Safety* consequences that affect the health or safety of pilots, other ship and port personnel, and local residents, including their work or home environments; and *Economic Consequences*, predominantly *Lost Revenue & Productivity* for the port and the regional economy, as well as loss or damage to ships and cargo. In general, most *Incidents* were associated with most *Consequences*. The exception to this is

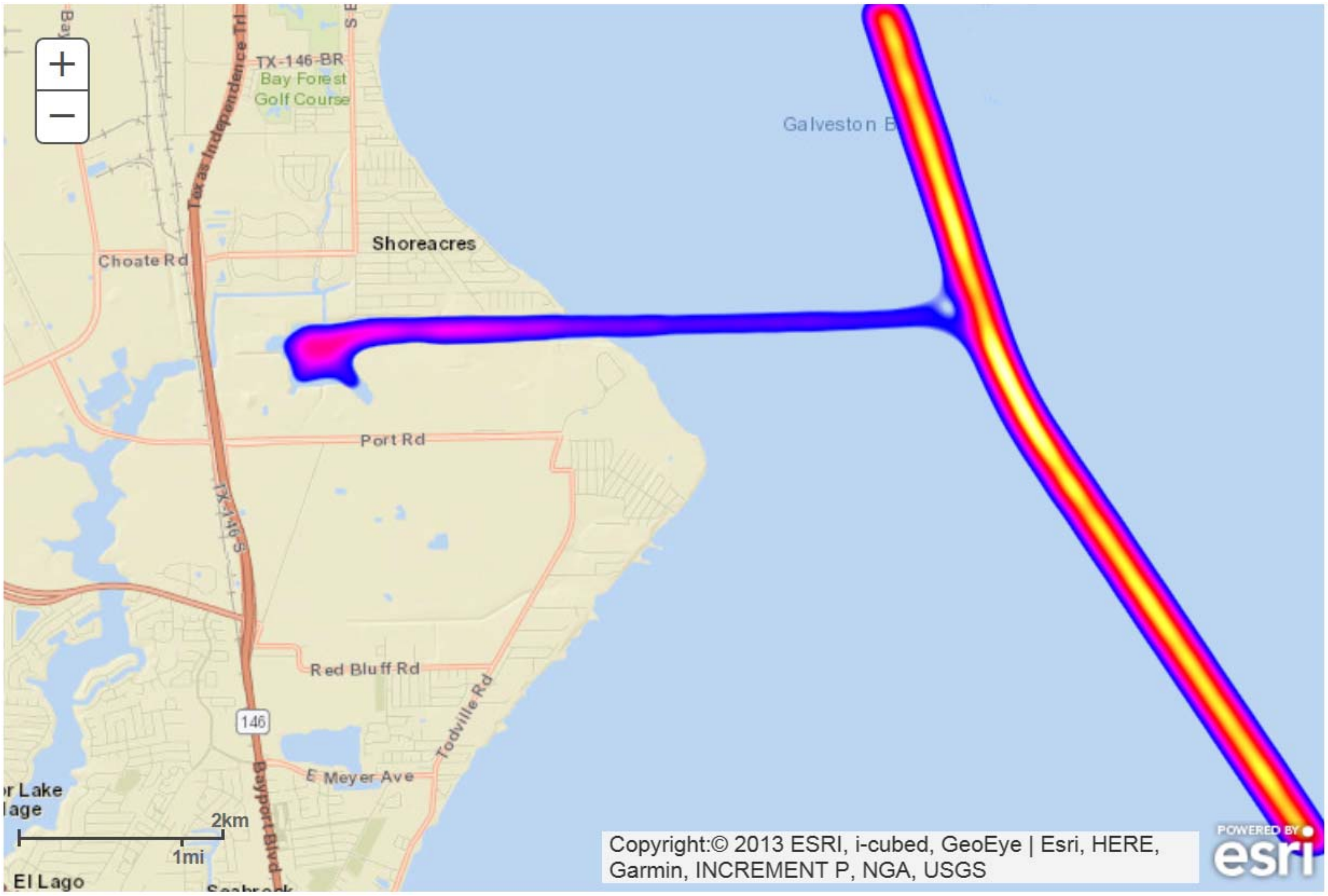

Fig. 5. AIS data showing "hot spots" along the HSC (map data © 2013 ESRI, i-cubed, GeoEye, Esri, HERE, Garmin, INCREMENT P, NGA, USGS)

Congestion & Closures, which are predominantly associated with *Lost Revenue & Productivity*, *Rerouting*, and *Air Quality* associated with increased congestion and idling at the mouth of the HSC.

Confirming Hot Spots via AIS Data

The AIS data are plotted in Fig. 5. Blue and red shading indicate fewer instances of AIS transmissions, with yellow shading indicating high amounts of AIS transmissions (or "hot spots"). As can be seen from the figure, a concentration is apparent at the intersection of the HSC and BSC, especially in the region just to the south of the intersection, where the HSC makes a slight angle. This confirms findings from the Expert Models, which indicate that congestion exists at this particular location in the HSC. Larger amounts of ship traffic increase the likelihood of collisions, allisions, groundings, and other negative events and therefore increase the overall navigation safety risk in this area.

An influence diagram developed through mental model interviews can be combined with AIS data to develop an understanding of the relationships between *Abilities* and *Incidents* and the influence that different *Measures* may have to enhance *Abilities* or reduce *Incidents*. This logic could be instantiated in an influence diagram representation in order to prototype conceptual designs of channel configurations or modifications to channel navigation policies to understand their effect. For example, widening the channel in a specific region increases movement affordance and therefore ability to successfully traverse the reach. This factor is independent of the maneuverability of the ship, but both influence the likelihood of allisions and collisions. For large ships with low maneuverability, widening the channel provides a substantial benefit in reducing risk, whereas for ships with high maneuverability, channel widening provides limited additional benefit (Fig. 6). *Measures* can be considered independently to understand which has the most influence on reducing the risk of *Incidents*, or in various combinations of *Measures* to the extent that interactions between *Measures* are understood and described, to understand the portfolio of *Measures* that most reduces risk of *Incidents*. This logic has been applied in several recent studies in the maritime context, linking human errors and other human factors (e.g., fatigue) with safety risks through

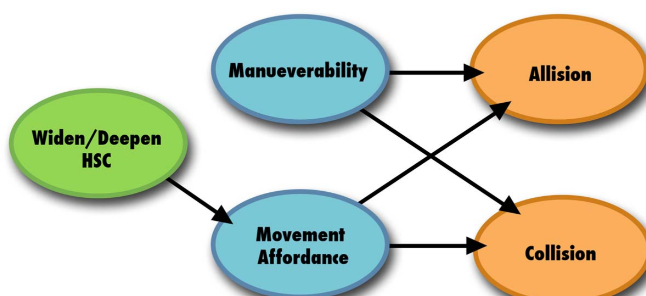

Fig. 6. Example influence diagram to evaluate conceptual designs of HSC channel modifications

Bayesian modeling approaches (Akhtar and Utne 2014; Martins and Maturana 2013; Hänninen and Kujala 2012; Salmon et al. 2012; Trucco et al. 2008; Eleye-Datubo et al. 2008).

Discussion and Conclusions

Mental model influence diagrams present an opportunity for summarizing knowledge and judgments from a collection of disparate subject matter experts in order to inform a decision. The result is a figure and associated narrative that enable an understanding of the main factors, relations, and influences between factors that can enable future decisions related to infrastructure design and other complex issues like those presented here (e.g., Linkov et al. 2004).

The influence diagram (e.g., Fig. 6), under certain conditions (Howard and Matheson 2005), can be used as the basis for structuring multicriteria decision analyses (MCDAs) (Linkov and Moberg 2011) of management or design alternatives (Kiker et al. 2005). Given a set of alternatives (e.g., conceptual channel design), MCDA provides a toolkit for comparing conceptual design alternatives based on multiple objectives by decomposing these objectives into a small number of decision making criteria that can be traded off against each other and with which metrics that define each alternative's performance on each criterion can be measured. Sensitivity analysis (Chu-Agor et al. 2011; Cullen and Frey 1999; Frey and Patil 2002; Saltelli 2002) can then be performed to determine when changes in assumptions regarding criteria tradeoffs, initial problem conditions, or other factors would lead to changes in preferences for one alternative or criterion compared to others.

Mental model influence diagrams can also be used to represent systems at different (nested) levels of abstraction. For instance, Fig. 2 represents how *Measures* influence *Issues* and *Abilities* in general, whereas Fig. 4 illustrates how specific types of *Measures* may address specific types of *Issues*. Fig. 6 addresses one specific *Measure* and its influence on *Incidents* by way of the abilities that the measure enhances as well as other *Measures* that can help to address those *Measures*.

These diagrams, depending on the level of detail, can also be used to make comparisons between different cohorts of experts or stakeholders. Engineers responsible for channel design may put more emphasis on *Measures* that optimize channel design, whereas budget officers may prefer *Measures* like better scheduling, operational restrictions for certain vessel classes, or insurance to reduce incidents or their impact. More detailed maps can be used to illustrate these differences by selectively including influences in the diagram based on the emphases of the cohort. Such contrasts can be used to identify the properties of AIS or other database data that are most useful to each cohort for purposes of decision making. Engineers may use AIS data to identify high-traffic areas for redesign; budget officers could use the tonnage associated with each vessel to estimate total economic productivity for specific ports of call in the channel.

This paper demonstrates an application of mental modeling for addressing incidents of concern in waterway navigation, with recommendations on how AIS data may be queried to address these concerns to minimize risks. The relationship between *Abilities* required to navigate a particular port and *Measures* that may serve to differentially enhance those *Abilities* will depend on the specifics of channel configuration, typical vessel traffic, and technologies available to port operators and pilots on a case-by-case basis. Specific to this case, the exercise provided a reference frame to compare long-standing structural alternatives (deepening and widening; Davis and Webb 2012; Waterway Simulation Technology 2011) to other structural alternatives as well as traffic management practices or other soft alternatives. This general approach may be applied to any engineered system where *Incidents* are known with their antecedents and data are available for that system that can help inform the frequency of those *Incidents* or the effectiveness of measures to reduce their severity and likelihood.

These methods are currently being used as USACE and partners work toward completing the recently initiated Houston Ship Channel 45-Foot Expansion Channel Improvement Project (HSC ECIP; U.S. Army 2016). For instance, directed analysis of AIS data was used to identify a region in the HSC where safety rules on bank-to-ship or ship-to-ship distance were violated on over 80% of ship passings (USACE 2016). This was a key factor in justifying correction of a navigation safety project deficiency (USACE 1982). The expert elicitation and AIS investigations were fundamental in validating anecdotal safety concerns expressed by stakeholders at reduced cost and time compared to more exhaustive analytical or simulation methods. This time savings allowed for faster deployment of corrective actions, therefore reducing exposure to the higher risks of ship collisions, including the potential for loss of life, property damages, and environmental damages, compared to maintaining the current channel configuration.

Influence diagrams and AIS can be used to develop light and efficient frameworks to rapidly prototype different conceptual design alternatives that can alleviate concerns like this while considering environmental, landowner, and other constraints in order to identify a very small number of design alternatives that should be considered for ship simulation or other further analysis. The result would be consistent with the USACE's S.M.A.R.T. Planning approach (Yoe 2014) of limiting the time and expense of planning studies by doing a better job of problem framing and testing feasibility of alternatives through screening approaches that allow alternatives to drop out of consideration quickly, rather than long and detailed approaches that provide a high-fidelity answer but reach comparable conclusions. An expert-informed mapping between process and data is critical for system improvement and rapid discovery of feasible design solutions. Mental modeling can play a key role in developing a simple and transparent representation of a process and make analogies to the information available that may inform decisions regarding that process.

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