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IMPROVING THE MANAGEMENT OF HUMAN AND ORGANIZATION ERRORS (HOE) IN TANKER OPERATIONS

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ABSTRACT

Human and organization errors (HOE) account for the vast majority of unanticipated significant problems associated with the design, construction, and operation of ships. Approximately 80 % of the problems are due to HOE, and approximately 80% of these can be traced to operations. The authors have developed a qualitative and quantitative approach to the evaluation of HOE in the operations of crude carriers. This paper summarizes the results of this work in the context of an analysis of the Exxon Valdez *incident. The HOE improved management approach is illustrated with evaluation of several alternatives to minimize the frequency of such incidents.*

INTRODUCTION

The study on which this paper is based is a three-year study to develop a "first generation" engineering procedure to help address and evaluate alternative improvements in the management of human and organization errors in the operations of marine systems. This study has accessed and evaluated existing databases that address major marine accidents including some 700 individual accident reports. Existing systems to classify and describe HOE have been evaluated and a system specially adapted to marine operations has been proposed. A complimentary qualitative - quantitative HOE analysis procedure has been developed. The procedure has been applied to two recent high consequence accidents: the grounding of the *Exxon Valdez* and the Occidental *Piper Alpha* platform explosions and fires. Two forward looking HOE studies have been conducted; one addresses tanker discharge operations and the other addresses platform crane operations.

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The following summarizes the primary observations that were developed during this study:

- There are three primary players in high consequence accidents: the front-line operators of the system (humans), the groups that are responsible for the management of the systems (organizations), and the physical elements (system).
- High consequence accidents result from a multiplicity or compounding sequence of break-downs in the human, organization, and system; often there are "precursors" or early warning indications of the break-downs that are not recognized or ignored.
- Systems (physical components) are generally the easiest of the three components to address; design for human tolerances and capabilities (ergonomics), provision of redundancy and damage / defect tolerance, and effective early warning systems that provide adequate time and alerts so that systems can be brought under control are examples of potential measures. Error inducing systems are characterized by complexity, close coupling, latent flaws, small tolerances, severe demands, and false alarms.
- Humans are more complex in that error states can be developed by a very wide series of individual characteristics and "states" including fatigue, negligence, ignorance, greed, folly, wishful thinking, mischief, laziness, excessive use of drugs, bad judgment, carelessness, physical limitations, boredom, and inadequate training. External (to the system) and internal (in the system) environmental factors such as adverse weather, darkness, smoke, and heat provide additional influences. Selection (determination of abilities to handle the job), training (particularly crisis management), licensing, discipline, verification and checking, and job design provide avenues to improve the performance of front-line operators.
- While the human and system aspects are very important, the organization aspects frequently have over-riding influences; corporate "cultures" focused on production at the expense of quality, ineffective and stifled communications, ineffective commitment and resources provided to achieve quality, excessive time and profit pressures, conflicting corporate objectives, and counter-quality and integrity incentives are often present in "low reliability" organizations. Generally, these aspects are the most difficult to address. Experience indicates that high reliability organizations tend to improve, while low reliability organizations do not improve rapidly, if at all.
- The most important part of the HOE evaluation process is *qualitative*; a realistic and detailed understanding of the human, organization, and system aspects and potential interactions must underlie the entire process. Quantitative aspects provide an important framework in which to evaluate the potential effectiveness of proposed "fixes" and to examine the detailed interactions of human, organization, and system components.
- There is no marine system HOE database that can be relied upon to give accurate quantitative indications of the frequencies of accident contributors; in the case of specific accident scenarios, existing databases frequently give misleading indications of causes and consequences. Complex interactions are frequently not determined or lost in the reporting. Study of past high consequence accidents can provide important insights into the complex interactions of humans, organizations, and systems and can provide the basis for development of generic "templates" for evaluation of other similar systems. Study of "near misses" can show how potentially catastrophic sequences of actions and events can be interrupted and brought under control. There is no generally available database or archiving system for "near miss" information.
- An adequate and understandable quantitative analysis system exists to assist evaluations of HOE; probability based "influence diagramming" has proven to be able to show the complex interactions and influences and efficiently produce quantitative indices that can indicate the effectiveness of alternative HOE "fixes." Because of the lack of accurate and

definitive objective data to serve as input to such quantitative models, structured "index" models have been developed to allow encoding subjective judgment into the evaluation of probabilities.

- A reasonable and workable HOE classification system has been developed. This system should provide the basis for development of future marine operations accident reporting systems. Investigators need to be well trained in the evaluation of human and organization factors in marine accidents. An industry wide computer database system needs to be developed to improve the efficiency of accident reporting and analysis of results. Information on both accidents and "near misses" need to be incorporated into this database.

- The primary objective of HOE analyses should not be to produce numbers. The primary objective of HOE analyses should be to provide a disciplined and structured framework that is able to produce insights and information that can lead to improvements in the management of HOE.

A GORDIAN KNOT

The principal focus of post-accident (or post catastrophe) investigations has been on performance failures that immediately preceded an accident. These are termed *active failures:* human errors or violations having an immediate impact on the integrity of a system. More recently, however, the scope of accident inquiries has widened considerably to also include *latent failures* committed in design, management, and organization [Reason, 1990]. This broader scope of accident investigation is recognized in the model presented here (Figure 1), particularly in Figure 2 which lays out the active failures, and Figure 3 which addresses latent failures.

Latent failures in technical systems--human errors or violations committed within the design, management, and organization of large scale systems--have recently been identified, and compared to resident *pathogens* in the human body which combine with local triggering factors (i.e., life stresses, toxic chemicals, etc.) to overcome the immune system (i.e., system safety measures) and produce disease (i.e., errors):

> *Like cancers and cardiovascular disorders, accidents in defended systems do not arise from single causes. They occur because of the adverse conjunction of several factors, each one necessary but none sufficient to breach the defenses...As in the case of the human body, all technical systems will have some pathogens lying dormant within them* [Reason, 1990: pg. 74].

The likelihood of an accident, or of a system's propensity for error, can therefore be described as a function of the number of pathogens in the system. The more abundant the pathogens, the greater the probability that some of them will encounter just that combination of local triggers necessary to complete a latent accident sequence. Further, the more complex the system, the more pathogens it will contain. The key assumption, however, is that *resident pathogens can be identified proactively, given adequate access and system knowledge* [Reason, 1990]. A qualitative analysis of the events leading to the grounding of the *Exxon Valdez* identified a number active failures, some of which are identified in Figure 2, and pathogens, some of which are identified in Figure 3.

When *Exxon Valdez* hit Bligh Reef just after midnight on March 24, 1989 she was holed in eight of her eleven cargo compartments and two ballast tanks. Most of the cargo loss occurred during the first eight hours after grounding. Thirty minutes after the grounding 115,000 of the 1,263,000 barrels were lost. A total of 258,000 barrels, or eleven million gallons, were lost in all. Many of the elements represented in the formal model are suggested by the story of what happened.

Our discussion will focus only on possible latent factors to leaving the Traffic Separation Scheme (TSS) and failing to return. A complete analysis would recognize the involvement of many parties over a long period of time, and a number of other behaviors. Table 1 summarizes the primary contributors to the deviation from the TSS by the *Exxon Valdez* crew and are described in this section.

Deviation from the TSS

A number of external factors potentially contributed to this act. While the weather was good, one physical factor was the possibility that an ice floe had moved into the outbound TSS. Other factors possibly came into play.

Deviation might have reduced travel time, an economic factor. Deviation was not uncommon, suggesting that a culture of reliability was possibly not in place. But it also suggests that the checks and balances often used in systems to insure that required behaviors are obtained did not exist. External sources might have warned against deviation. As we discuss later, the Coast Guard Vessel Traffic Service had atrophied over time in that equipment maintenance and VTS staffing were both limited. Both of these limitations might have been overcome if a pilot had stayed with the ship until she came closer to clearing the Sound.

In addition, behavior at sea the night of the grounding indicated that various parties to the situation failed to act on some fairly clear warning signals. Ironically, three months before this accident, the only other major spill in the twelve years of the Trans-Alaska Pipeline operation occurred when the *Thompson Pass* released 1,700 barrels of oil. Other accidents had happened other places, yet all parties to tanker operation in Valdez Harbor seemed oblivious to these warning signals.

Failure to return to the TSS

The immediate active errors contributing to this failure were the actions of the third mate and the helmsman on the bridge. Both failed to recognize the ship's location.

A number of latent failures underlie these active failures. Again, due to time constraints only a few are mentioned here. Exxon Shipping Company recognized that the helmsman had limited capability. The company had been unsuccessful with the union in limiting his duties so he could not take the helm of the ship. Both the company and the union had some responsibility to examine their bargaining and negotiation within the framework of improving safety in tanker operation.

While either a training or selection problem (or both) may be additional pathogens, the context within which these people operated strongly suggests yet others. The captain was off the bridge and before departing had asked the third mate if he felt he could take the ship out of the Sound. It is possible the pressure the captain felt to complete paper work helped him come to a poor decision to be off the bridge. But certainly, the captain's experience and training should have suggested too him that the "proper" answer to asking a subordinate, "can you do the job?" is "yes." Again, apparently expediency overrode the operation of a safe and reliable culture in determining behavior.

We turn from this limited illustration of the complex qualitative analysis underlying model development to the model itself.

MODELING THE TANKER GROUNDING

Based on the results summarized in the foregoing section, the accident events are categorized in to underlying/contributing, direct, and compounding factors. The primary contributing factors are shown in Figure 1 and summarized as follows.

Underlying / Contributing Factors

Event: *Exxon Valdez* deviates from the outbound *traffic separation scheme* (TSS) to avoid an ice floe in the outbound lane.

Causes: The deviation of from the TSS was not an isolated incident though was not recommended by either the operators nor the USCG. At the time of the grounding there had been a reduction of billets at the USCG Marine Safety Office in Valdez. On the night of the grounding the vessel traffic center (VTC) crew had not established *Exxon Valdez* on the radar nor kept in radio communication after the vessel departed from the Valdez Narrows.

As the vessel deviated from the lane it was placed on automatic pilot (it is questionable as to whether the auto pilot was on until just before the grounding).

The master left the bridge leaving only the third mate in command which is in violation of Exxon Shipping operating policy. At the time of the grounding, Exxon was in the process of determining how to reduce the crew sizes aboard the vessels even though crews frequently are excessively fatigued and overworked. The chief mate was too tired to take his watch at 12 midnight since he had spent the day coordinating the loading of the vessel at the Alyeska terminal. The company had conducted no studies on the human effects of reducing crew sizes.

Conditions: Ice floe conditions in the outbound lane of the TSS was a precursor to the decision to deviate from the TSS.

Direct Factors

Event: The vessel does not return to the TSS and grounds on Bligh Reef.

Causes: The USCG had problems with the radar system in Prince William Sound at the time of the grounding. It is questionable as to whether the VTS personnel could properly monitor the *Exxon Valdez* on the radar. Though no radar communication may have been possible, vessel and VTS personnel had not kept in radio communication to determine the track of *Exxon Valdez*.

The third mate was unable to determine the location of the vessel just before the grounding. His lack of knowledge, training, and experience under these operating conditions had made it difficult to make proper navigation decisions.

Conditions: The time of day was approximately midnight at or about the time of a change of watch on the bridge.

Compounding Factors

Event: Captain Joseph Hazelwood, the master of *Exxon Valdez*, attempts to lodge or dislodge the vessel from Bligh Reef resulting in the compounded loss of cargo.

Cause: Captain Hazelwood may have attempted to push the vessel onto the reef to keep the vessel from capsizing. This may have been in violation of laws limiting the discharge of cargo into the water.

Conditions: At the time of the grounding the tide was dropping. This may have led to the decision to stabilize the vessel on the rocks to prevent capsizing.

Model Representation

This model incorporates critical factors both aboard *Exxon Valdez* and at the Vessel Traffic Center (VTC) in Valdez. The underlying/contributing event is the deviation of the vessel from the Traffic Separation Scheme (TSS). The grounding of the vessel is the direct/initiating event and the attempt to dislodge the vessel from the rocks is the subsequent compounding event that led to the additional loss of cargo. Figure 2 diagrams the influences between error solicitors (events, decisions, and actions) leading to the grounding.

Intermediate events, decisions and actions are related to the primary events and directly influence the grounding events. Conscious actions and decisions were made by the master to: (1) deviate from the TSS, (2) depart from the bridge during transit, and (3) place the tanker on auto pilot and "load up" program. Each of these actions and decisions are represented as decision nodes.

The direct influences of HOE and environmental causes on primary and intermediate events, decisions and actions are shown in the final representation in Figure 3. The grounding model forms a basis from which the influence diagram template is developed.

Influence Diagram of Vessel Grounding or Collision

Once a vessel deviates from a specific TSS within navigable waters, potential hazards (vessel traffic, reefs, currents, etc.) can greatly increase the risk of transit. An underlying factor in the events leading to the grounding of *Exxon Valdez* was the decision to deviate from the TSS. Thus the accident has been classified under groundings and collisions. In analyses of tanker groundings and collisions, the following general questions are addressed in developing the influence diagram template models.

- Did the vessel deviate from a previously established traffic scheme? If so, was it a conscious decision to do so? It is assumed in the model that conscious decisions were made to deviate from the scheme and was not inadvertent.
- Is the path and location of the vessel being properly monitored? Monitoring can be either internal (vessel crew) or internal and external (vessel traffic center). The monitoring of the vessel is directly related to whether a grounding or collision will occur.
- Were environmental factors involved in the decision to deviate from the traffic separation scheme (ice in the lane, waves, tide, etc.)? Was vessel traffic a factor in the decision to deviate from the traffic scheme?
- Are ship system factors involved in the grounding of the vessel? For example, the vessel may loose power, steering, or navigation capabilities? (This issue has been of particular concern in such tanker groundings as the *Amoco Cadiz* off the coast of France and the *Braer* off of the Shetland Islands.)
- Were human and organizational errors involved in the decision to deviate from the traffic separation scheme and/or monitoring of vessel path?

The influence diagram shown in Figure 4 is representative of the primary contributing factors for a vessel grounding or collision. The grounding of *Exxon Valdez* falls within this general class of accidents. The primary contributors are described below and the variables are summarized in Table 2.

- *Environmental conditions.* The environmental operating conditions are described as a state variable since the conditions will vary from time of day to season.
- *Human errors.* Human errors are affected by the environmental operating conditions, the deviation from the traffic lane (non-routine) and vessel traffic (stress and non-routine). These are described as a probabilistic variable.
- *Deviates traffic separation scheme.* The vessel may deviate the traffic separation scheme as a result of environmental factors or vessel traffic. The deviation is represented as a probabilistic variable.
- *Vessel traffic.* Vessel traffic will be variable dependent upon the location and inherent variability in shipping throughput. Vessel traffic is represented as a probabilistic variable to accommodate these contributing factors.
- *Monitor vessel path:* Monitoring of vessel path and location is affected by deviation from the TSS and human errors. Vessel paths are closely monitored if deviation occurs.
- *Vessel operation system failure.* Vessel operating system failure is included to account for possible loss of systems critical to the safe operation of the vessel. This includes navigational devices, power plant, or any other critical operating system. The failure of these systems are variable and are represented as a probabilistic node.
- *Grounding or collisions.* Groundings or collisions are directly affected by vessel traffic, TSS deviation and monitoring of vessel path, and operational system failure. The failure event is considered probabilistic upon the contributing factors.
- *Spill.* The possibility of a spill is contingent upon the grounding or collision of the vessel and its speed at the time of the casualty event.
- *Vessel speed.* The vessel speed will have a direct effect upon the outflow of oil upon grounding or collision.
- *Spill cost.* The cost of the spill is represented as an expected value node to be evaluated at the end of the diagram.

Evaluating the Grounding and Collision Model

In evaluating the influence diagram shown in Figure 4, the two particular values of concern are the probabilities of groundings or collisions given human errors and the expected costs of a spill. Human error probabilities were derived using the *Human Error Safety Index Method* (HESIM) developed by Moore and Bea (1993). The HESIM integrates error inducing parameters (error solicitors) leading to a potential accident event. The error solicitors are organizational, human, task, system, and environmental factors. The HESIM is further described in Appendix B. The USCG casualty database and human error modeling for nuclear power plants were also used to determine contributing factors influencing tanker casualties (e.g., machinery and equipment failures, human error task errors, etc.) [CASMAIN, 1990; Swain & Guttmann, 1983]. Spill size data were determined from VLCC collision and grounding models [Det Norske Veritas, 1991]. The probabilities of spill sizes for a grounding or collision of a standard VLCC are provided in Table 3.

Environmental operating conditions will differ from season to season and vessel traffic is dependent upon location of the study. Sensitivity analysis may be performed on these variables to determine the impact of the variations in the conditions. For the model the nominal values for environmental operating conditions and vessel traffic in the Valdez port are summarized in Table 4.

Human errors are dependent upon three primary contributing factors: (1) vessel traffic, (2) vessel deviation from the TSS, (3) and the environmental operating conditions. The three contributing factors. The human errors at the operator level are described for a well operated tanker fleet with a high commitment to safety and resources made available for safe operation. Heuristic judgments were used to determine the frequencies of HOE's under the various operating conditions.

Vessel groundings and collisions are directly dependent upon vessel path monitoring, deviation from the TSS, vessel system failure. It is assumed if the vessel path is properly monitored, human intervention will prevent a collision or grounding course. A vessel operating system failure is presumed to be only 1 out of 100 transits (.01). Vessel operating speeds in the areas of vessel traffic are presumed to be 5 knots 70% of the time and 30% of the transits are at 10 knots.

Spill costs are estimated at $30,000 per barrel (bbl).[1] These estimates are based on costs of clean up, legal, and miscellaneous costs. Evaluating the influence diagram results in a the annual probability of groundings and collisions and probabilities of human errors given the grounding or collision are shown in Table 5.[2] There is a 1.1% chance of either a collision or grounding per year. The largest contributors to the grounding and collision events are lack of communication or information, violations, and mental-physical lapses. These three contributors account for over 50% of the human error related causes.

The Oil Pollution Act of 1990

Since the grounding of *Exxon Valdez*, the most influential changes for tanker operations in U.S. territorial waters has been the *Oil Pollution Act of 1990* (OPA 90). OPA 90 addresses a wide variety of tanker operation issues and are representative of current HOE management alternatives [Noble, 1993]. As an overview, Title IV of OPA 90 [Connaughton, 1990]:

- mandates that the Coast Guard tie into the National Driving Register to detect individuals with drunk driving convictions;
- increases Coast Guard authority to deny or revoke mariner licenses and documents;
- authorizes removal of incompetent personnel;
- increases Coast Guard authority to deny entry of foreign vessels into the U.S. waters on the grounds of deficient manning;
- limit crew work hours aboard tankers to 15 hours per day but no more than 36 hours in any 72 hour period;
- mandates the Coast Guard conduct studies on vessel traffic and tanker navigation;

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[1] The cost of the *Exxon Valdez* was approximately $30,000 per barrel spilled. Many contributing factors affect the cost per barrel; such as spill location, size, type of oil (product or crude), clean-up procedure, legal fees, etc. Cost estimates can be modified to incorporate as many contributors as wanted. The spill costs could have been modeled as a probabilistic node to incorporate the uncertainty involved in determining the total costs. However, for simplicity we have set a deterministic value of $30,000 per barrel spilled.

[2] The human error probabilities are the probabilites that the error was the primary contributor. Other human errors may be observed in the accident sequence.

- requires all new tanker builds to be double-hulled in addition to the phasing out of existing tankers beginning in 1995 and concluding in 2010; and,
- require the Coast Guard to designate areas where two licensed personnel are required on the vessel bridge and tug escorts are necessary.

There are three fundamental complimentary forms of HOE management alternatives to improve operational reliability: 1) directly addressing HOE through HOE management programs, 2) changes in operational procedures, and 3) development of human error tolerant systems. The HOE management alternative described here is a change of operational procedure. The HOE management alternative modeled is the required tug vessel support specified by the *Oil Pollution Act of 1990* (OPA 90).

Figure 5 is an influence diagram representing the addition tug support to tank vessels for transit through navigable waters. The tug support is presumed available during all environmental conditions except for high seas (waves). In the event of a vessel system failure the tug support is available. It is presumed that the tug(s) escort the vessel and are monitor the vessel path.

The effect of the tug support is an increase in the probability of reliable monitoring of vessel path and a reduction of the probability of grounding or collision. The estimated reductions in human error frequencies were developed through expert judgments and reference to studies performed for nuclear power plant operations [Swain & Guttmann, 1983]. It is assumed the primary reductions in human errors at the operator level are in violations, communication and information, mental-physical lapses, and knowledge, training, and experience. Tanker crews are less willing to violate transit laws when tugs are present (regulating and policing). Communication and information are more available to the tanker crews, since the tug crews are knowledgeable of the waters being transited. The experiences of the tug crews also reduces problems of knowledge training and experience of the tanker crews. Mental and physical lapses are less likely to occur if proper communication and information as to the status of the tanker vessel is being exchanged between tanker and tug crews.

Evaluating the influence diagram in Figure 5 to find the probability of groundings and collisions and probabilities of human errors given the grounding or collision are shown in Table 6. The probability of collisions have been reduced by 57% and the probability of groundings are reduced by 75% if tug support is available. There is a net expected benefit of $11,309,096 if tug support is available.

Substantial reductions in the incidence of human errors as the primary accident related cause are observed. The incidence of violations as primary cause have been reduced by 75% for collisions and 56% for groundings. Communication and information errors and mental-physical lapses have been reduced by more than 82% for collisions and 67% for groundings. Initiations of accidents resulting from human system interface errors for collisions and groundings are reduced by 85% and 75% respectively.

The addition of tug escorts for vessels for specified transits reduce the incidence of grounding or collision events. Other alternatives may be addressed to determine the impact upon the system.

CONCLUSIONS

We have developed an engineering procedure to systematically address HOE in operations of tankers. The case study of the grounding of the *Exxon Valdez* has been used as a framework from which to develop qualitative and quantitative models (influence diagram templates) to address groundings and collisions which are similar in nature. The template models are used to assist engineers, operators, regulators, and managers in evaluating alternatives to reduce the impacts of human and organizational errors in the operations of marine systems.

The template models involve both qualitative and quantitative assessments. Due to the deficiencies in existing HOE databases, the quantitative models rely heavily on experience and judgments. Our experience with applications of this procedure to operations of marine systems indicates that if qualified and motivated personnel are involved in the analyses, the procedure can produce important insights on how best to utilize safety resources to help reduce the incidence and effects of HOE in operations of marine systems

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APPENDIX A: INFLUENCE DIAGRAMS[3]

One method of developing accident framework models for PRA analysis is through the use of *influence diagrams*. Influence diagramming is a form of PRA modeling which allows great flexibility in examining HOE and HOE management alternatives. There are distinct advantage for using influence diagrams as an alternative to standard event/fault tree analyses. In standard decision tree analysis, decisions are based on all preceding aleotory and decision variables [Howard & Matheson, 1981]. However, all information is necessarily available to a decision maker. In addition, information may come from indirect sources or may not come in the specific order in which the decision tree is modeled. It is not necessary for all nodes to be ordered in an influence diagram. This flexibility allows for decision makers who agree on common based states of information, but differ in ability to observe certain variables in the diagram modeling [Howard & Matheson, 1981]. Influence diagrams are able to organize conditional probability assessments required to determine unconditional probabilities of failures of specified target events [Phillips, *et al.*, 1990].

As described by Howard (1990) (see Figure A-1), the components of an influence diagram are: (1) *decision* and *chance nodes*, (2) *arrows*, (3) *deterministic nodes*, and (4) *value nodes*. Decisions are represented by square nodes which can be a continuous or discrete variable or a set of decision alternatives. Uncertain events or variables are represented by circular or oval chance nodes. Chance nodes can be continuous or discrete random variables or a set of events. Arrows indicate relationships between nodes in the diagram. Arrows entering a chance node signify that the probability assignments of the node are conditional upon the node from which the arrow originated. Deterministic nodes are those in which outcomes depend deterministically upon its predecessors. A value node is designated by the author to be: "the quantity whose certain equivalent is to be optimized by the decisions" of which only one node may be designated in the diagram. Value nodes may be a distribution of possible values. This is represented by a rounded edge single-border node. The value node may also be represented as the expected value. These nodes are represented by a rounded edge double-border rectangle.

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[3] The *influence diagram* is defined by Bodily (1985) as:

> *"...a display of all of the decisions, intermediate variables, outcome attributes that pertain to a problem, along with the influence relationships among them. By influence we mean a dependency of a variable on the level of another variable."*

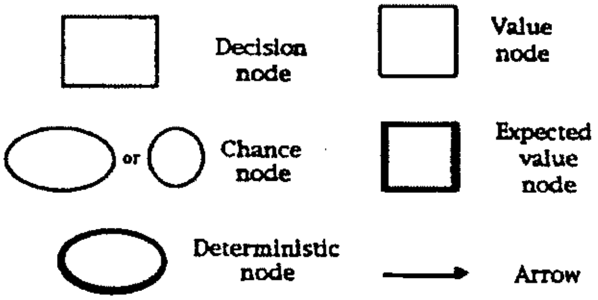

Figure A-1: Influence diagram characterizations

APPENDIX B: HUMAN ERROR SAFETY INDEX METHOD (HESIM)

Safety (risk) index methods are described as a modified quantitative risk assessment in which key risk contributors are identified, assessed and assigned numerically weighed values [Gale, 1993]. In absence of probabilistic data, determining safety indices allow for examination of the relative risks. As probabilistic information becomes available, comparisons are drawn between safety indices and probabilities of failure. This verification of risk indices leads to better probabilistic assessments if data is not available by implementing a safety index.

The HESIM accounts for contributing human, organizational, and system errors leading to human errors at the operational level [Moore & Bea, 1993]. The HESIM integrates error inducing parameters (error solicitors) leading to a potential accident event. The error solicitors are organizational, human, task, system, and environmental factors. The concept for the HESIM is to incorporate error factors from four general contributors: (1) organizational, (2) human, (3) system complexity, and (4) the operating environment. Organizational errors are further distinguished into top-level and middle-front-line management, and regulatory contributors. Human factors include the stress and "routineness" of the activity. Operating environment is differentiated into external operating environment (wind, waves, temperature, etc.) and internal operating environment (noise, fumes, smoke, etc.).

The *human error safety index* ($SI(HE_i|EDA_q)$) (Eqn. 1) for a particular event, decision, or action q (EDA_q) is the product of four safety indices: (1) the *organizational error index* ($SI_{HE_i|OE}$), (2) the *human factor index* ($SI_{Hum\ factor}$), (3) the *system index* (SI_{System}), and (4) the *environmental index* ($SI_{Environ}$).

$$SI[HE_i|EDA_q] = SI_{HE_i|OE,EDA_q} * SI_{HE_i|Hum\ factor,EDA_q} * SI_{HE_i|System,EDA_q} * SI_{HE_i|Environ,EDA_q} \quad \text{..........(B-1)}$$

Each safety index is assigned a value between 0 and 1 ($0 < SI < 1$) dependent upon the contribution of that factor upon the human error for particular events, decisions, or actions. The assigned values are acquired from accident data and heuristic judgments.[4]

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[4] For further detail on the HESIM, see: Moore, W.H. & Bea, R.G. (1993) *Management of human error in operations of marine systems: Final project report.*

Table 1: Contributing factors to the grounding of *Exxon Valdez*

Deviation from TSS
• Possibility of ice floe • Reduction in travel time • Organizational culture of reliability was not in place • Checks and balances non-existent • VTS equipment maintenance and staff limited • Failure to pay attention to warning signals
Failure to return to TSS
• Third mate and helmsman fail to recognize location • Helmsman's limited capability: training and selection • Management and union negotiation activities fail to see safety as primary concern • Master's failure to monitor third mate

Table 2: Outcomes within each node of vessel grounding-collision influence diagram

vessel speed *5 kts* *10 kts* **vessel traffic** *light* *heavy*	**spill size (bbls)** *0-178,000* **grounding /collision** *none* *grounding* *collision*	**environment / operating conditions** *none* *lane obstruction* *waves* *wind* *tide*	**human errors** *none* *violations* *communication/information* *job design* *mental/physical lapse* *knowledge/experience/training* *human/system interfaces*
vessel operating system condition *operating* *fail*	**deviates vessel TSS** *no TSS deviation* *TSS deviation*	**monitor vessel path** *monitor* *no monitor*	

Table 3: Conservative discharge estimates for tanker groundings and collisions for fully loaded VLCC single-hull design[5]

Casualty event	Probability	Spill size in barrels (bbls)
Collision	.22	12,750
	.28	25,500
	.25	38,250
	.20	59,497
	.05	178,000
Grounding (5 kts)	.2	25,500
	.35	35,700
	.3	51,000
	.15	76,500
Grounding (10 kts)	.08	71,400
	.5	91,800
	.3	112,200
	.12	122,400

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[5] Standard VLCC design with a 330,000 dwt capacity, 315 m long, 57.2 m breadth, 20.8 meter draft, .83 block coefficient.

Table 4: Nominal probabilities for tanker operating conditions

Environmental operating conditions:	**Probability**
none	.900
lane obstruction	.002
waves	.005
wind	.010
tide	.083
Vessel traffic	
light	.75
heavy	.25

Table 5: Annual probabilities of groundings and collisions and associated human errors for each event[6]

Event	**P[Event]**	
collision	.007	
grounding	.004	
Human Error	**P[human error| collision]**	**P[human error| grounding]**
none	.46	.42
violation	.08	.09
communication - information	.14	.15
job design	.08	.07
mental - physical lapse	.11	.12
knowledge - training - experience	.06	.07
human system interface	.07	.08

Table 6: Annual probabilities of grounding or collision event with tug support[7]

Event	**P[Event]**	
collision	.003 (-57%)	
grounding	.001 (-75%)	
Human Error	**P[human error| collision]**	**P[human error| grounding]**
none	.88 (91%)	.81 (93%)
violation	.02 (-75%)	.04 (-56%)
communication - information	.02 (-85%)	.03 (-80%)
job design	.03 (-63%)	.03 (-57%)
mental - physical lapse	.02 (-82%)	.04 (-67%)
knowledge - training - experience	.02 (-67%)	.03 (-57%)
human system interface	.01 (-85%)	.02 (-75%)

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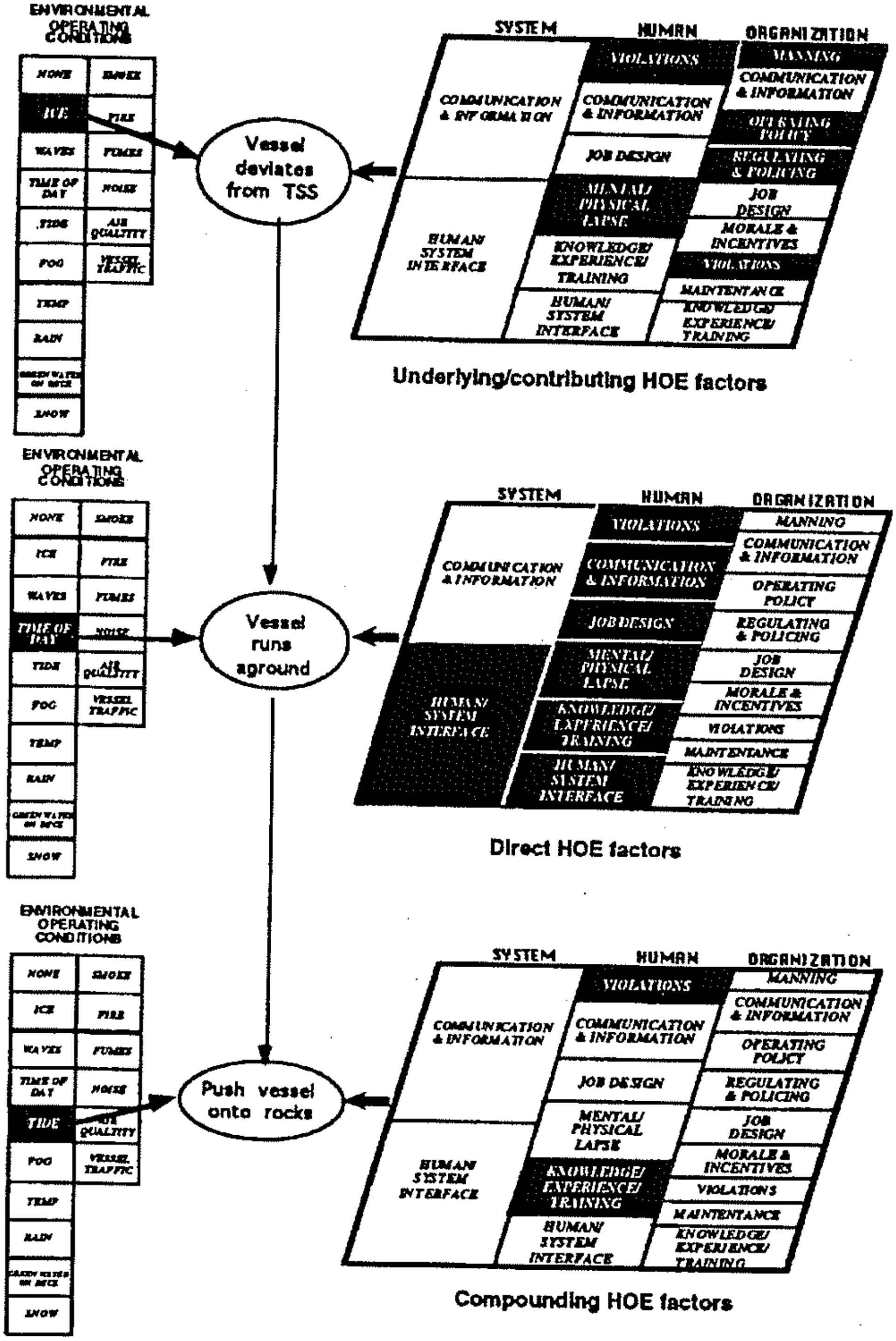
[6] These probabilities account for the primary causes of the accident. There is a substantial compounding of human errors.

[7] Values shown in parentheses account for the percent change in error being a contributing factor to the casualty event with the implementation of tug support for tanker transits.



Underlying/contributing HOE factors

Direct HOE factors

Compounding HOE factors

Figure 1: HOE influences on the events involved in the grounding of *Exxon Valdez*

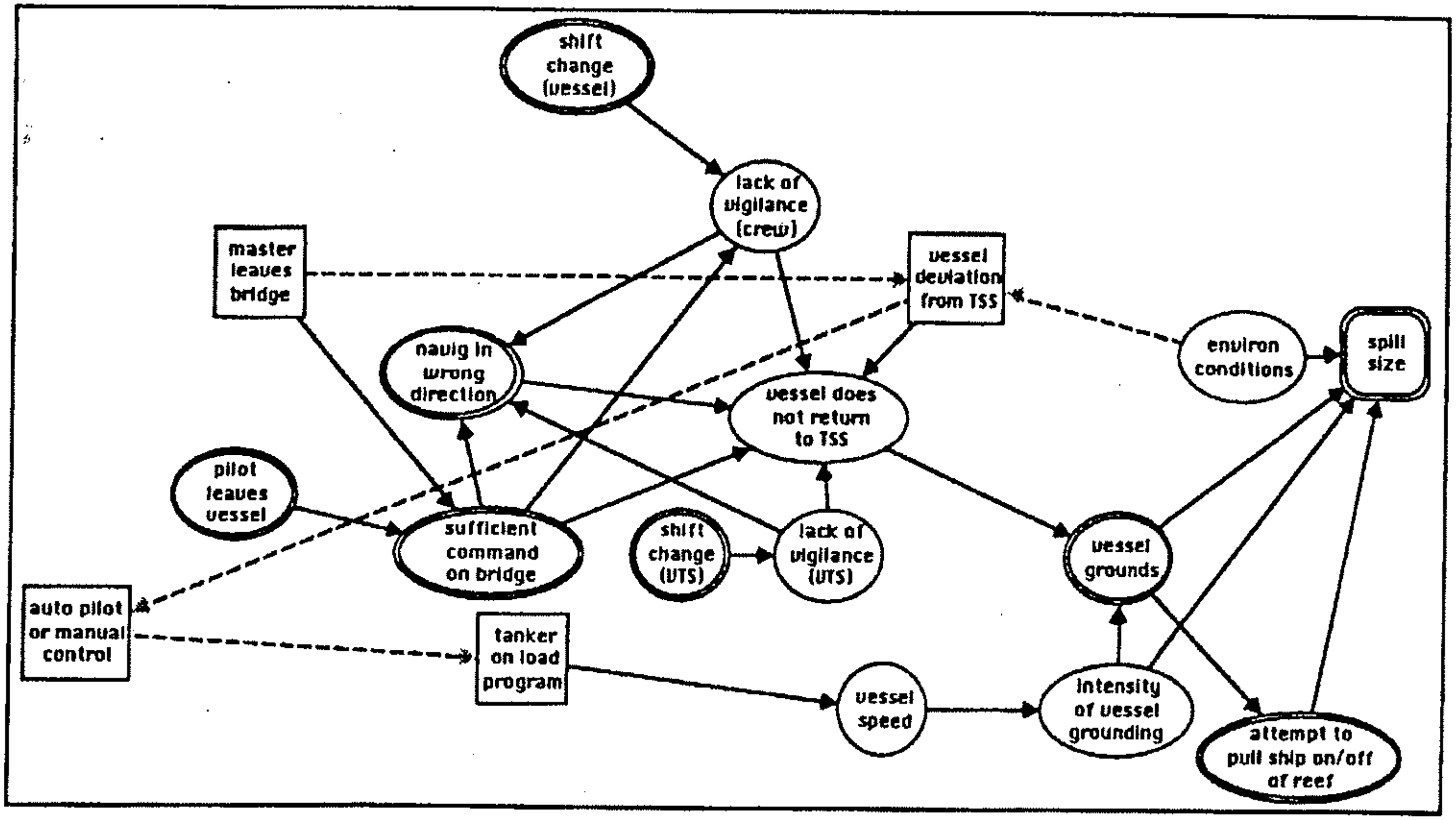


Figure 2: Influence of events and decisions leading to grounding of *Exxon Valdez*

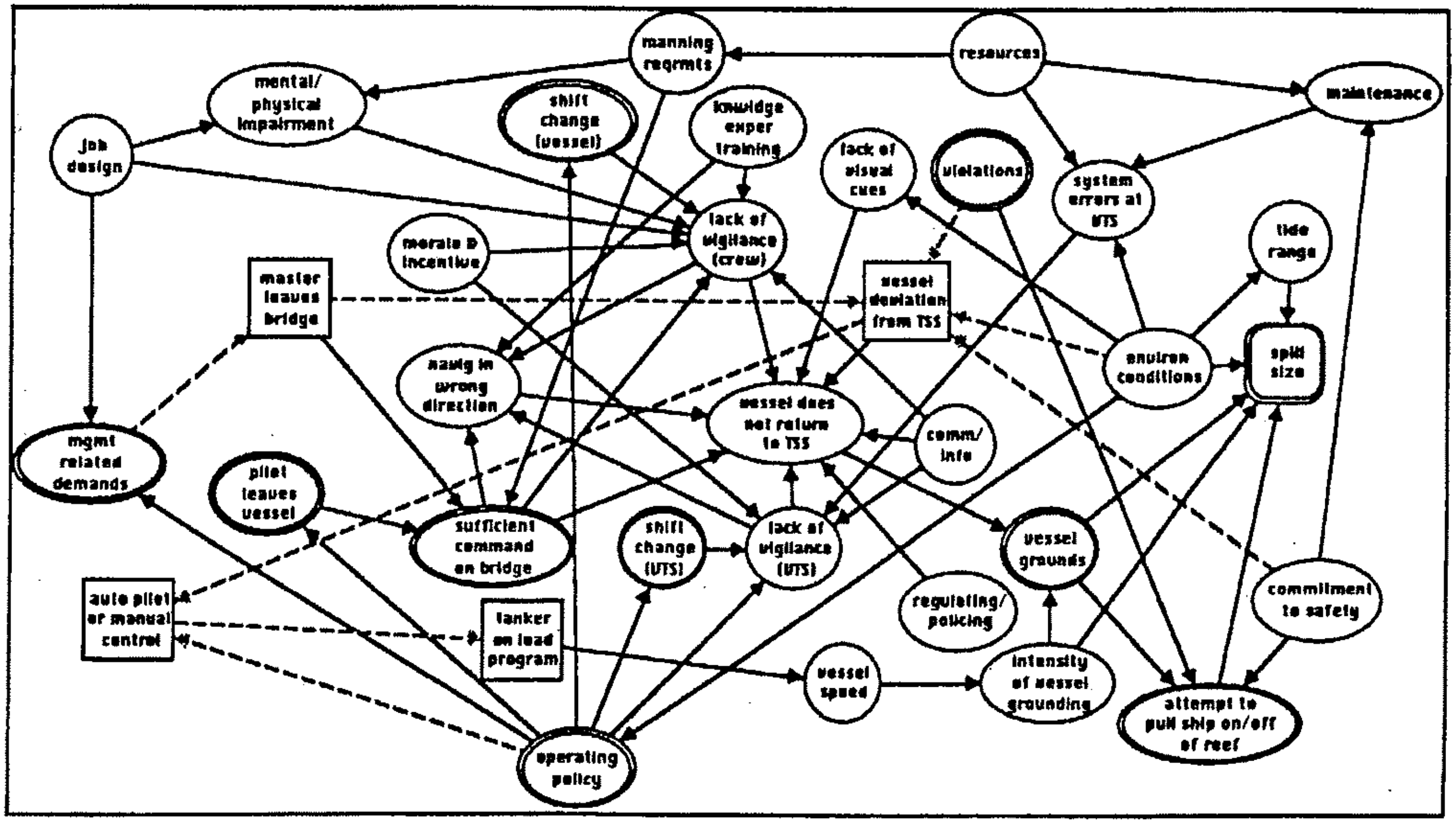


Figure 3: Influence diagram representation of factors leading to grounding of *Exxon Valdez*

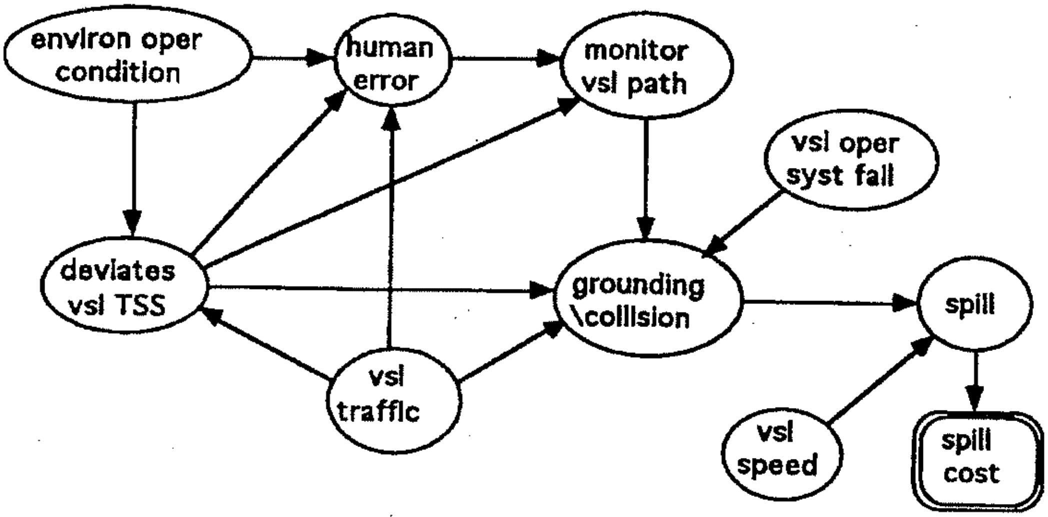


Figure 4: Influence diagram model of major factors involved in tanker grounding or collision

p 14 results
p 8,9 background

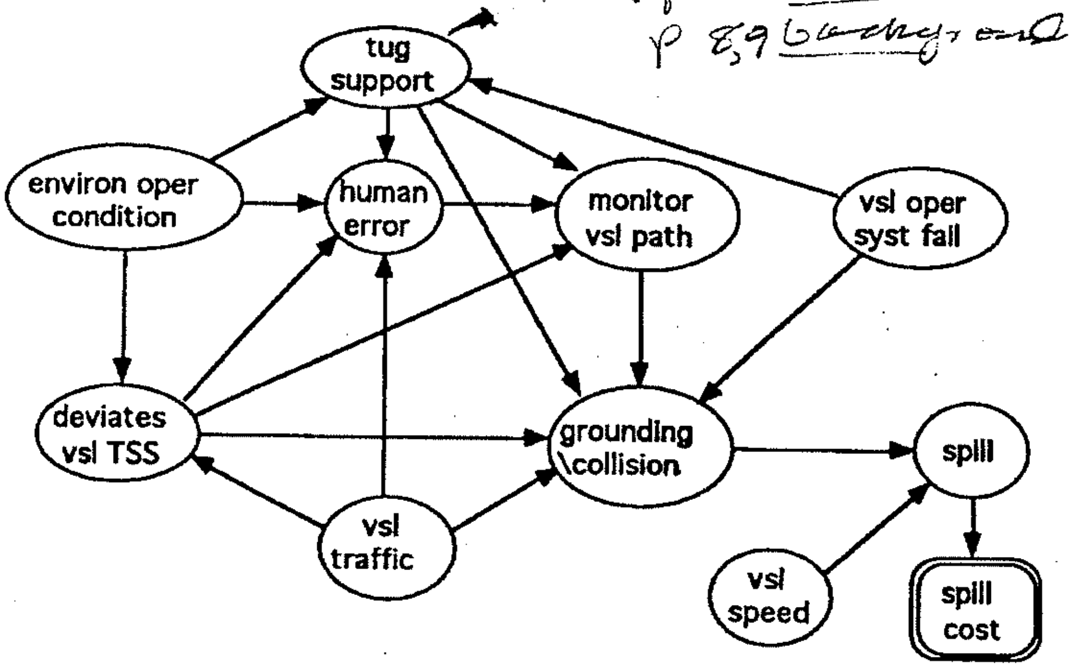


Figure 5: Influence diagram to model the effects of tug support