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Assessing the Impact of Management and Organizational Factors on the Risk of Tanker Grounding

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ABSTRACT

Management and organizational factors have contributed, directly or indirectly, to many tanker accidents. These factors are frequently not considered in human reliability analysis, probabilistic risk assessment or accident investigations. In order to successfully incorporate effective and efficient measures to prevent accidents, a systematic approach including all important root causes and variables must be utilized. The objective of this paper is to present a probabilistic risk model for tanker grounding which includes management and organizational factors and their relationship to human error. Work on this model continues the development of an earlier model which applied risk assessment methodologies from the nuclear power industry to quantify the impact of human error on the probability of tanker grounding. This approach is extended to consider the effect of management and organizational factors on human performance shaping factors, and ultimately on human error. This effect is examined and quantified using expert opinion and the Analytical Hierarchy Process (AHP). Management and organizational factors found to have the greatest impact on the probability of grounding are identified and compared to factors emphasized by the International Safety Management (ISM) Code.

KEY WORDS: Grounding, risk, human error, International Safety Management (ISM) Code, Analytical Hierarchy Process (AHP)

INTRODUCTION

A number of highly visible oil spills have increased the public's awareness of the dangers involved in transporting oil at sea. As a result, the marine industry has come under increased pressure to reduce the risk of such accidents. Traditionally, design deficiencies and individual error have received the most attention when assessing tanker risk and investigating tanker accidents. More recently the importance of management and organizational factors (MOFs) in ship operations has been realized (Boniface and Bea, 1996a & b; Moore and Bea, 1995).

Human error has a substantial impact on the reliability of complex systems, and it may occur in any phase of design, construction or operation. Due to the large number of accidents caused by human error, success in reducing tanker risk depends directly on measures to improve human performance (NRC, 1994). MOFs greatly influence both physical and human elements involved in the design and operation of a ship. The ability of ship systems to perform in a satisfactory manner depends on proper design, maintenance, and operation, all of which are directly affected by management. Similarly, the crew is greatly affected by policies, procedures, and decisions made by management.

The International Safety Management (ISM) Code recognizes this relationship, and requires vessel operators to develop and implement a safety management system (SMS). In order to meet the requirements of the ISM Code, a ship operator is required to identify factors that involve the most risk, and to develop preventive or corrective measures for these factors. This paper analyzes a generic and simplified series of processes and tasks for tanker route planning and piloting in a notional waterway. By applying this framework and methodology to the processes and routes for a specific tanker or fleet of tankers, a ship operator may identify critical MOFs contributing to their tanker risk.

INTERNATIONAL SAFETY MANAGEMENT (ISM) CODE

The ISM Code is the international standard for the safe management and operation of ships (IMO, 1994). It requires companies to provide for safe practices in ship operation, and insure a safe working environment. They must identify, evaluate, and establish safeguards against all identified risks. They must continuously improve the safety management skills of personnel ashore and onboard their ships, including preparation for emergencies related both to safety and environmental protection. Here, "companies" means ship owners or any other organization or person who assumes responsibility for operation of the ship from the ship owner. The ISM Code mandates that ship owners and operators have a safety management system (SMS) which ensures that both safety and pollution prevention are central in operations. The code introduces the concept of self-regulation including the requirement for internal audits and management reviews.

The MOFs specifically emphasized by the ISM Code include:

- Organizational Culture
- Safety Culture
- Organizational Learning
- Formalization
- Coordination of Work
- Communication
- Personnel Selection
- Training Process

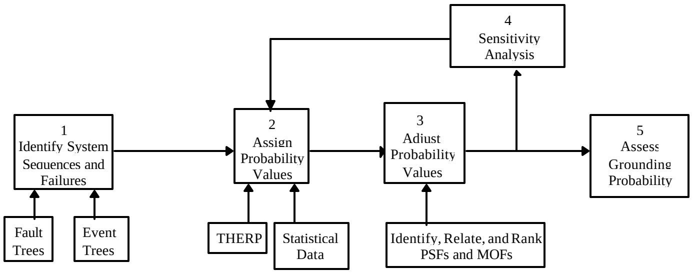

Figure 1. PRA Process Including Management and Organizational Factors

PROBABILISTIC RISK ASSESSMENT (PRA)

This paper builds on a grounding model, developed in a previous study (Amrozowicz, 1996 & 1997), which estimates the probability of tanker grounding. It employs the method of probabilistic risk assessment (PRA). PRA is a method for identifying and quantifying hazards and solutions with the greatest risk-reducing potential. The previous model is expanded to include Performance Shaping Factors (PSFs) and MOFs. Figure 1 illustrates the process used to build the model, and assess the impact of MOFs.

PRA was developed in the nuclear industry. It is based on fault and event tree methodology. The fault and event tree approach consists of discrete logical diagrams explicitly showing the casual relationships within a system which determine the probability of accident scenarios. The Technique for Human Error Rate Prediction (THERP) is a method employed to quantitatively predict individual human error probabilities (HEPs). The product of this method is a set of HEP tables. The original data used to support the THERP data tables were developed at Sandia National Laboratories for the nuclear power industry.

Basic HEPs are estimated for generic tasks which collectively comprise a specific series of tasks or process. The planning, piloting, and decision processes involved in grounding are defined by a series of standard tasks which are common to many processes. It is assumed that error rates for these basic tasks are independent of their broader application and context. This assumption permits the application of the THERP data assembled in (Swain and Guttmann, 1983) to the calculation of tanker risk.

The current grounding PRA model does not explicitly model the dependencies of human error and system failure on management and organizational factors. In order to assess the impact of organizational factors on tanker operations, the following process is utilized (Embrey, 1992; Apostolakis, 1996):

1. Determine human errors that lead to tanker grounding and assign probability values (HEPs).
2. Identify major immediate influences on HEPs. These are the PSFs. Determine and quantify their effect.
3. Identify important MOFs which influence PSFs and quantify their effect.

The quantification of these influences is accomplished using the Analytical Hierarchy Process (AHP) and is represented in a multi-attribute value function. Figure 2 illustrates the conceptual HEP/PSF/MOF relationship.

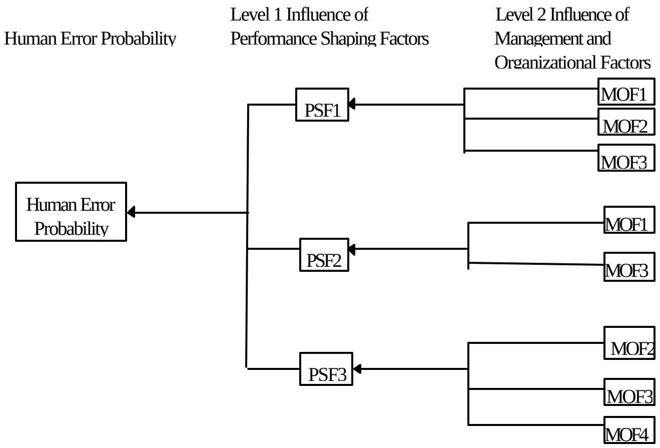

Figure 2. Conceptual Relationship of PSFs and MOFs to Human Error Probability

ANALYTIC HIERARCHY PROCESS (AHP)

The AHP is used to determine the relative influence of the PSFs and MOFs on human error relevant to grounding. The AHP is a methodology developed by Saaty (1996) for solving multi-attribute decision problems. It uses a hierarchical structure to abstract, decompose, organize and control the complexity of decisions involving many attributes, and it uses informed judgment or expert opinion to measure the relative value or contribution of these attributes and synthesize a solution. Pairwise comparison and a maximum eigenvalue approach extract and quantify this relative value. The method allows and measures inconsistency in value measurement, and is able to consider quantitative and qualitative attributes.

A hierarchy is a simplified abstraction of the structure of a system used to study and capture the functional interactions of its attributes, and their impacts on total system behavior or performance. It is based on the assumption that important system entities or attributes, which must first be identified, can be grouped into sets, with the entities of one group or level influencing the entities of only one other group or level. One can conceptualize a hierarchy as a bottoms-up synthesis of influence on the top level behavior of a system, or as the top down distribution of influence of top level behavior to low level attributes. Alternatives are compared in terms of the lowest level attributes and this comparison is rolled up through hierarchy levels to an assessment of relative overall system behavior or performance.

The first step in building an AHP hierarchy is to identify critical attributes effecting the decision or system behavior. The level of detail of these attributes depends on the decision being made. These attributes are then organized into a hierarchy structure which follows a systematic breakdown or categorization.

Next, the relative influence of each attribute on system performance and attribute values for each alternative is estimated. Saaty recommends a nine level dominance scale for the pairwise comparison of attribute influence on higher level attributes. This results in a ratio scale comparison of attributes. The AHP synthesizes and evaluates the consistency of redundant information and calculates best fit relative values.

Although the AHP was developed primarily for comparison of management alternatives, it has also proven to be a useful method for application in Multiattribute Value Theory (MAVT, Belton, 1986). The AHP provides a structured method for deriving an additive weighted value function, and by careful application can also be used to derive attribute value or utility using pairwise comparison vice the more traditional lottery comparison approach.

In this research, hierarchies are constructed for each of the major HEPs contributing to tanker grounding and identified in the grounding fault and event trees. With a specific HEP at the top level of the hierarchy, PSFs and MOFs impacting the specific HEP are identified and included in the hierarchy. Expert opinion is obtained using pairwise comparison of PSFs and MOFs to extract and quantify a relative value matrix and function.

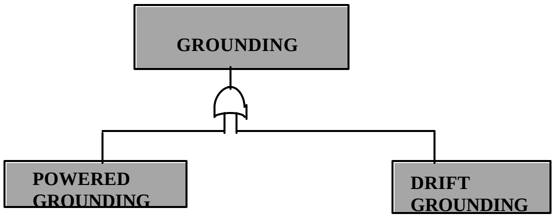

Figure 3. Top Level of Grounding Fault Tree

GROUNDING MODEL

Tanker groundings result from either powered grounding or drift grounding, defined as follows (DNV, 1995):

- Powered grounding - An event in which grounding occurs because the tanker proceeds down an unsafe track, even though it is able to follow a safe track, due to errors related to planning or piloting failure.
- Drift grounding - An event in which grounding occurs because the tanker follows an unsafe track because it is unable to follow a safe track due to equipment failure, anchor failure, assistance failure, or adverse environmental conditions.

The top portion of the fault tree developed for grounding is shown in Figure 3. The simple Boolean expression for the probability of grounding, resulting from this structure of the fault tree, is:

$$P_{Grounding} = P_{PoweredGrounding} + P_{DriftGrounding} \qquad (1)$$

Powered Grounding

The powered grounding portion of the grounding fault tree is shown in Figure 4. The fundamental failures involved in a powered grounding are failures in passage planning and in piloting. HEPs and event trees are used at various levels of the fault tree to calculate fault probabilities. In order to determine the probability that a planning error is made given that published planning information is correct, an event tree, Figure 5, is used. To carry out passage planning satisfactorily, the most current charts and other navigational information must be available and updated to reflect the most recently published changes. To update navigational charts, the mariner must check all applicable publications. The process involved in checking periodicals for relevant changes is assumed analogous to following procedures with no check-off provisions. Following the checking of periodicals, the changes are transferred to the charts. The mariner develops a list with the appropriate changes which is similar to a check-list or procedure that a reactor technician may use. Therefore the human error related to correctly entering or plotting the changes in the appropriate charts is assumed to be similar to following procedures with check-off provisions. The task of determining waypoints for the passage involves studying the updated charts to determine the route the vessel should follow in order to get from origin to destination. The task

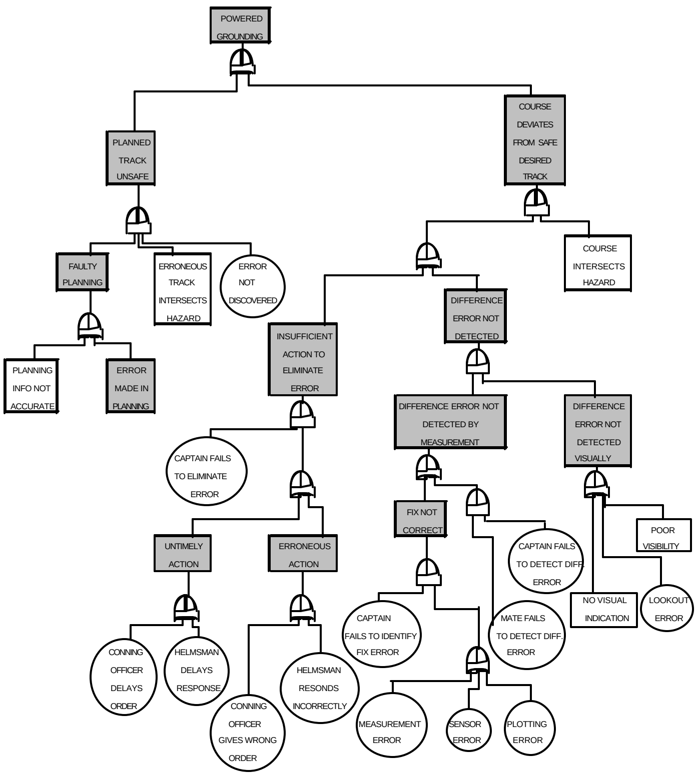

Figure 4. Powered Grounding Fault Tree

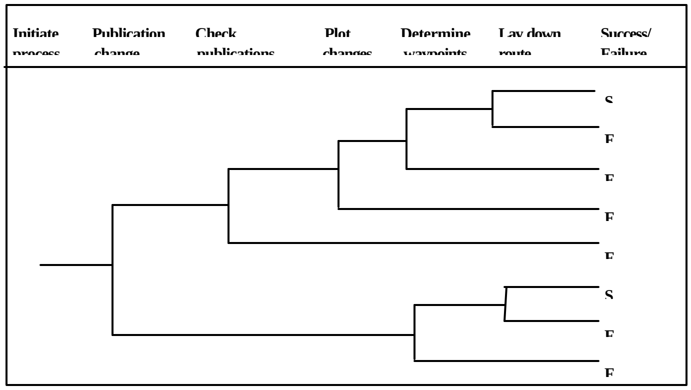

Figure 5. Event Tree for Estimating Planning Error

involved in determining waypoints is assumed to be analogous to writing a procedural item. The task of laying down the route involves plotting the waypoints and determining the locations of any hazards to navigation. This process requires the use of dividers and simple mathematical calculations, which is similar to a nuclear reactor technician's use of a micrometer, i.e., writing a procedural item with simple arithmetic. Many of these basic navigational tasks are changing as new technology and methods replace older manual methods. This will require fault trees and probabilities presented here to be adjusted, but the basic framework and approach remains valid.

The process of laying down the route is followed by review and verification which provides a mechanism for recovery. It is possible that after the process of plotting the route, the plotter may recognize an error. This verification process functions as a recovery event, which is analogous to the event of checking a chart recorder with limits. Similarly, the approval process requires that the master also verify the validity of the route. This task is analogous to hands-on checking. A summary of the various HEPs related to the route plan are listed in Table 1.

Table 1. HEPs for Passage Planning (Swain and Guttmann, 1983)

Maritime Task	Analogous Nuclear Power Plant Task	Standard HEP	Range
Check publications for changes	Following procedures with no check-off	0.003	0.0010-0.009
Plot changes	Following procedures with check-off	0.001	0.0003-0.003
Determine waypoints	Writing procedural item	0.003	0.0006-0.015
Lay down route	Writing procedural item with arithmetic	0.010	0.0030-0.030
Recognize faulty track	Check chart recorder with limits	0.002	0.0007-0.006
Master properly verifies	Hands-on type checking	0.010	0.0020-0.050

The probability that the process results in a faulty plan, calculated using the equation derived from the event tree and mean HEP values, is:

$$\begin{aligned} P_{FaultyPlan} = 1-[&P_{PublicationsAffectPlan} \cdot \\ &(1-P_{CheckPubError})\cdot(1-P_{PlotError})\cdot(1-P_{WaypointError}) \cdot \\ &(1-P_{LayRouteError})+(1-P_{PublicationsAffectPlan}) \cdot \\ &(1-P_{WaypointError})\cdot(1-P_{LayRouteError})] = 1.336 \cdot 10^{-2} \end{aligned} \qquad (2)$$

After laying down the route, the mate checks to make sure it is correct, and finally the master verifies the route. It is assumed that there is no disagreement between the master and mate after one or the other detects an error. Once an error is discovered it is assumed that the route plan is correct. The probability that errors are made in the planning process is:

$$\begin{aligned} P_{PlanningError} = P_{FaultyPlan} \cdot P_{MateFailsRecogFaultyPlan} \cdot \\ P_{MasterFailsRecogFaultyPlan} = 2.673 \cdot 10^{-7} \end{aligned} \qquad (3)$$

Referring again to Figure 4, the probability that the information used in planning the route is inaccurate must also be determined. Inaccurate navigational information may result from:

- Unmarked channel hazards
- Channel not maintained properly
- Inadequate weather information
- Improper navigational aid location

A study analyzing data for four of the busiest ports in the US (San Francisco Entrance, New Orleans, Baton Rouge, and Valdez) found that there were 19 tanker accidents caused by incorrect planning information between 1986 and 1990 (Amrozowicz, 1996). The accident quotient, which is the number of accidents due to faulty navigational information divided by the number of transits, was found to be $4.58 \cdot 10^{-4}$. This value provides an estimate for the probability of inaccurate navigational information causing an accident.

The probability that the erroneous route actually intersects a hazard is assumed to be 0.5. This value is only notional, and should be corrected to reflect a particular route. This probability is already included in the probability of inaccurate information causing an accident, but must be included separately with the planning error probability. The probability that a planning error is not discovered while underway is assumed to be equal to the error in hands-on type checking. Finally, the probability that the ship follows an unsafe route is given by:

$$P_{RouteUnsafe} = (P_{IncorrectInformation} + P_{PlanningError} \cdot P_{IntersectHazard}) \cdot P_{NotDiscovered} = 4.581 \cdot 10^{-6} \quad (4)$$

Grounding also results when the ship’s course deviates from a safe planned route while under power, and the course intersects a hazard. This fault is caused by piloting error. The sequence of events in the piloting process is as follows:

1. The actual course deviates from the route plan
2. A difference error between the actual course and the route plan is generated
3. A fix is taken and plotted
4. The difference error is detected
5. A correct course change is ordered
6. The helm responds

As a ship follows its planned route, deviations are constantly monitored and corrected. This deviation is called a difference error or cross track error, and should not be confused with human error as modeled in the fault tree. In this paper it is assumed that piloting error which results in grounding must occur when the ship is outside of its channel and a significant difference error exists. An analysis methodology similar to that used with the planning process is followed for calculating the piloting error probability. The Figure 4 fault tree, standard HEPs and hardware reliability data are used to estimate the probability of not detecting a difference error when it exists and the probability of insufficient action to eliminate the difference error when it is detected. These probabilities are used to calculate the probability of a piloting error when or after taking a fix outside the channel:

$$P_{PilotingError/outside} = P_{DifferenceErrorNotDetected} + P_{DifferenceErrorDetected} \cdot P_{InsufficientAction} = 8.963 \cdot 10^{-5} \quad (5)$$

The result of this piloting error depends on the characteristics of the waterway and the relative timing of the error along the track. Notional waterway, ship, and ship track characteristics were chosen for this paper. The notional waterway is illustrated in Figure 6. The channel is 200 meters wide, has two lanes, and requires 10 left turns and 10 right turns. The ship is assumed to maintain a speed of 12 knots, and the average piloting cycle is assumed to be 3 minutes, i.e., the fix rate is 1/3 minutes^{-1}. The route is along the center of the right hand lane in the two-lane channel. The total transit distance is 116 km, and the total transit time (T) is 5.2 hours. The location of the ship relative to the center of the channel is specified by a normal distribution around the center of the right hand lane with a mean of -50 meters, and a standard deviation of 25 meters (Pedersen, 1992):

$$f(z) = \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma}} \cdot e^{\frac{-(z-\mu)^2}{2 \cdot \sigma^2}} \quad (6)$$

where: $z = [-100,100]$; $\mu = -50$ m; $\sigma = 25$ m

Given this distribution, the probability that the ship is outside the channel during the transit is 0.023. Assuming that a radar fix is taken every 3 minutes, the average piloting error rate is:

$$\lambda_{PilotingError} = P_{PilotingError/outside} \cdot P_{outside} / 3\text{min} = 6.797 \cdot 10^{-7} \text{ errors/min} \quad (7)$$

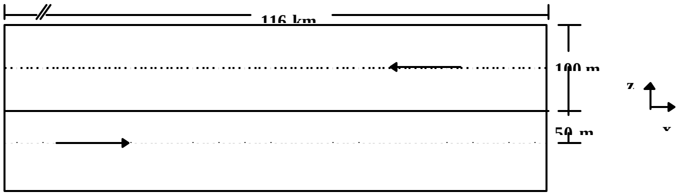

Figure 6. Notional Waterway

(Note: This is a notional and traditional scenario. The Global Positioning System (GPS) and Electronic Chart Display and Information Systems (ECDIS) update position about once per second and pilots depend on more frequent visual sightings. Actual equipment and process information must be included in any specific application of this methodology.) The probability that the course deviates from the direct or straight route plan is calculated assuming a Poisson process using Equation 7 for the average error rate. Failure on straight legs of the route is defined as making at least one piloting error during the time the tanker is outside the channel, or failing to take a fix before exiting the channel after missing a turn. The probability that the ship’s course deviates from a straight planned route is:

$$P_{CourseDeviatesStrPlannedRoute} = (1 - e^{-\lambda_{PilotingError} \cdot T}) = 2.123 \cdot 10^{-4} \quad (8)$$

In a left turn, the distance to the point where the tanker exits the channel may be approximated by 1/4 of the total channel width. Dividing this distance by the vessel speed, the resulting time until the tanker exits the channel in a missed left turn is 8.089 seconds. In a missed right turn, the distance to the point where the tanker will exit the channel may be approximated by 3/4 of the total channel width. Dividing this distance by the speed of the tanker, the resulting time until the tanker exits the channel in a right turn is 24.267 seconds. The probabilities that no fix is taken before the tanker is outside the channel during a missed left or a missed right turn, assuming a Poisson process, are:

$$P_{NoFixLeftTurn} = e^{-\lambda_{Fix} \cdot T_{UntilOutsideChannelLeftTurn}} = 0.956 \quad (9)$$

$$P_{NoFixRtTurn} = e^{-\lambda_{Fix} \cdot T_{UntilOutsideChannelRtTurn}} = 0.874 \quad (10)$$

The probability that the course deviates in a turn from the planned safe route, assuming that the probability of failing to turn is similar to that of following procedures with check off and the probability of the master failing to detect the failure is similar to that involved in hands-on checking, is:

$$P_{CourseDeviatesFromPlannedTurn} = 1 - [1 - P_{FailToTurn} \cdot P_{MasterFailsToDetectFailure} \cdot P_{NofixLeftTurn}]^{NumberOfLeftTurns} \cdot [1 - P_{FailToTurn} \cdot P_{MasterFailsToDetectFailure} \cdot P_{NofixRtTurn}]^{NumberOfRtTurns} = 1.830 \cdot 10^{-4} \quad (11)$$

The probability that the course deviates from the desired safe route, and that the actual course is unsafe, is then:

$$P_{UnsafeCourseDeviatesFromSafeRoutePlan} = (P_{CourseDeviatesStrPlannedRoute} + P_{CourseDeviatesFromPlannedTurn}) \cdot P_{IntersectsHazard} = 9.391 \cdot 10^{-5} \quad (12)$$

The total probability of powered grounding is then:

$$P_{PoweredGrounding} = P_{PlannedRouteUnsafe} + P_{UnsafeCourseDeviatesFromSafeRoutePlan} = 2.022 \cdot 10^{-4} \quad (13)$$

Drift grounding, as previously defined, is an event in which the tanker is unable to follow the planned, safe route. In order for drift grounding to occur, all of the following types of failures and conditions must occur:

- Unsafe winds/currents
- Assistance failure
- Anchor failure
- Loss of steerage way

These failure conditions are illustrated in the drift grounding portion of the grounding fault tree, shown in Figure 7.

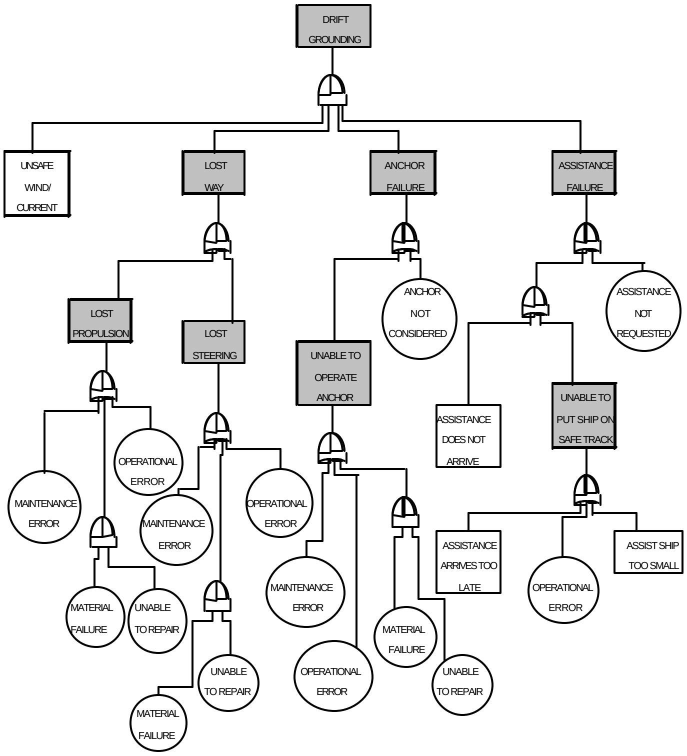

Figure 7. Drift Grounding Fault Tree

An analysis methodology similar to that used with the planning and piloting processes is followed for calculating the probability of drift grounding. Standard HEPs, hardware reliability data and actual grounding accident data are used to estimate drift grounding fault probabilities.

The resulting probability of drift grounding is:

$$P_{DriftGrounding} = P_{Unsafewindorcurrent} \cdot P_{LostWay} \cdot P_{AnchorFailure} \cdot P_{AssistanceFailure} = 5.063 \cdot 10^{-6} \quad (14)$$

The total probability of grounding is the sum of the probabilities of powered grounding and drift grounding:

$$P_{Grounding} = P_{PoweredGrounding} + P_{DriftGrounding} = 2.073 \cdot 10^{-4} \quad (15)$$

PERFORMANCE SHAPING FACTORS

HEPs used in estimating the probability of tanker grounding are specified by (Swain and Guttmann, 1983) as mean values within an uncertainty range. PSFs are used to interpolate within this uncertainty range and calculate a specific HEP value. They provide the link between MOFs and HEPs. The following important PSFs were considered in this analysis:

1. Inattention - The lack of full vigilance, or loss of attention, regarding responsibilities or tasks assigned.
2. Lack of Motivation - Lack of desire to perform required duties well (IMO, 1996)
3. Poor Physical Condition - Fatigue, physical fitness, physical problems, and the overall well-being of the personnel.
4. Poor Performance Ability - Level of training, experience, and the aptitude of personnel.
5. Inadequate Knowledge of Procedures, Standards, and Regulations
6. Conflicting Motives Regarding Performance - Inadequate knowledge or confusion with respect to priorities and company goals regarding safety of performance, quality of performance, schedules, profitability, etc.
7. Poor Architectural Features. - Poor engineering design of the ship, its subsystems, environmental controls, and human-machine interfaces (IMO, 1996)
8. Lack of Perception or Inadequate Situational Awareness - An individual does not properly realize the existence of a problem or situation or misdiagnoses the problem or situation once it has been perceived.
9. Lack of Communication/Inadequate Exchange of Information - The failure to communicate, or exchange information, regarding problems and tasks aboard ship and ashore.
10. Unaware of Responsibilities - Inadequate knowledge of specific tasks required, or confusion in lines of authority and responsibility.
11. Hazardous Natural Environment - Motion sickness in open waters. In restricted waters, the channel width, traffic density, and availability of navigational aids are major factors that may create stress. The suddenness involved in having to adjust from the open ocean scenario to the situation in restricted waterways (IMO, 1996).

MANAGEMENT AND ORGANIZATIONAL FACTORS

MOFs directly or indirectly influence PSFs. The safety culture inherent in an organization influences all the MOFs and it is considered inherent in all elements of the analysis and not treated as an individual variable. The following describes important MOFs that effect PSFs, and indirectly effect HEPs:

1. Workload - Work hours and breaks as determined by the overall amount of work that is to be done, work and overtime policies, level of manning, and physical or mental capability of the crew.
2. Formalization - Well-identified rules, procedures, and standardized methods for routine and emergency activities.
3. Coordination of Work - Planning, division, integration, and implementation of work-related activities among individuals or groups of individuals (Davoudian and Apostolakis, 1994)
4. Organizational Culture - The personnel's shared perception of the organization including traditions, values, customs, practices, goals, and socialization processes that endure over time. The "personality" of the organization.
5. Benefits - The level of pay or salary and other benefits such as insurance and retirement programs. The overall distribution of the company's financial resources.
6. Physical Resources - Tools, equipment, supplies, and facilities to perform required tasks. Includes the absence, shortage, inappropriateness, and storage of resources, as well as the difficulty in obtaining the resources.
7. Quality of Life - Standard of living including the quality and cleanliness of living quarters and the overall environment, the quality and variation of food and entertainment, adequate lighting, heating, cooling, and ventilation.
8. Performance Evaluation - The degree to which personnel are provided with fair assessments of their work-related behavior.
9. Company Programs - Programs related to the overall well-being of the crew including alcohol and drug programs, fitness programs, health programs, etc.
10. Personnel Selection - The degree to which hired personnel have requisite knowledge, experience, skills, ability and compatibility to perform a given job.
11. Personnel Turnover - Movement of crew members among various vessels, which results in crew members operating a vessel with which they have little or no experience.
12. Training Programs - The quality of training in which personnel are provided with the requisite knowledge and skills to perform tasks safely and effectively.
13. Supervision - The level of oversight of the activities of personnel and the degree to which personnel are provided on-the-job training.
14. Time Urgency - Situations in which personnel perceive schedule pressures while completing tasks.
15. Organizational Learning - the degree to which the organization uses knowledge gained from past experience, both from the company itself or the industry, to improve future performance.
16. Communication - Includes external, inter-departmental, and intra-departmental communication, both formal and informal.

INFLUENCE OF MOFS AND PSFS ON CRITICAL HEPS

The relationship of PSFs and MOFs to the following critical HEPs is examined using the AHP and expert opinion. Critical HEPs considered in this analysis are:

1. Failure to Initiate and Carry Out Planning Correctly - Includes four tasks: failure to check publications and notices without error (following procedures with no check-off), failure to properly enter the changes on the charts (following procedures with check-off), failure to determine safe waypoints (writing a procedural item), and failure to lay down a safe route (writing a procedural item with arithmetic).
2. Failure of Master to Detect and Correct Errors (hands-on checking)
3. Failure to Correctly Read Radar Ranges (read quantitative information from a digital display)
4. Failure to Correctly Plot Ranges on a Chart (error of commission in recording readings)
5. Failure to Detect Difference Error (checking readings with limits)
6. Failure to Order Required Course Change (nonpassive task errors of commission)
7. Failure to Respond to Ordered Course Change (failure to recall two items, or instructions, given orally)
8. Failure to Drop Anchor in an Emergency (diagnosis following an abnormal event)
9. Failure to Request Assistance in an Emergency Situation (diagnosis following an abnormal event)

Expert opinion was collected using pairwise comparison questionnaires. Experts included merchant marine, US Coast Guard and US Navy officers. The questionnaire required 20 to 30 minutes to complete. HEP/PSF/MOF hierarchies and results are shown in Figures 8 through 11 for two HEP cases.

INCORPORATING MOFS INTO THE GROUNDING MODEL

In order to quantitatively determine the MOF performance of a particular company relative to the probability of tanker grounding, and which MOFs have the largest impact on grounding, HEP/PSF/MOF value functions are included in the grounding model. The HEP uncertainty ranges are utilized to determine the range of MOF influence. The general form for this value function is:

$$HEP = HEP_{low}+\Delta HEP\cdot[(W_{MOF1})\cdot R_{MOF1} + (W_{MOF2})\cdot R_{MOF2}+\ldots..+ (W_{MOFX})\cdot R_{MOFX}] \qquad (16)$$

where:

ΔHEP = Uncertainty Range

W_{MOFx} = MOF_x Weight (decimals summing to one from AHP results)

R_{MOFx} = Rating of MOFx with Respect to Specific Company

In Figure 12, a comparison is made between MOF ratings of inadequate and excellent. A value of 1 is used for a rating of inadequate, a value of 0 is used for a rating of excellent and a value of $\Delta HEP_{mean}/\Delta HEP$ is used for a rating of adequate. Each MOF value is increased from 1 to 0 while other MOFs are held at their mean value.

The probability of grounding is $3.00\cdot 10^{-3}$ for a company with all MOFs rated as inadequate, $2.07\cdot 10^{-4}$ with all MOFs rated as adequate (93.1% reduction from inadequate), and $1.5\cdot 10^{-5}$ with all MOFs rated as excellent (99.55% reduction from inadequate). This is a remarkable potential improvement, and demonstrates, in rough quantitative terms, the significant impact of MOFs on tanker grounding.

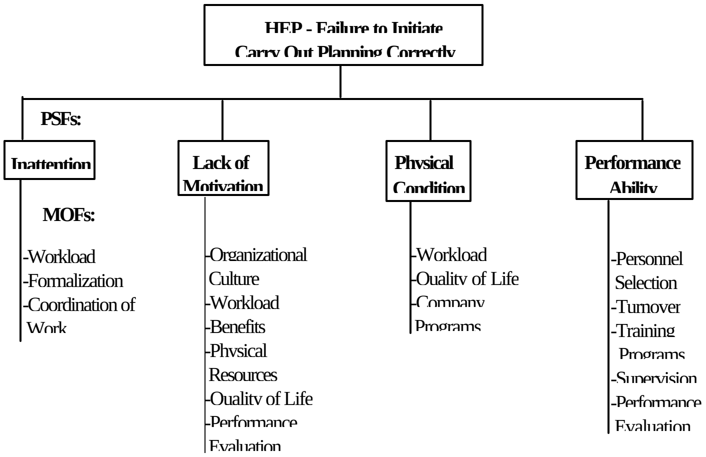

Figure 8. Factors Influencing HEP to Initiate and Carry Out Planning

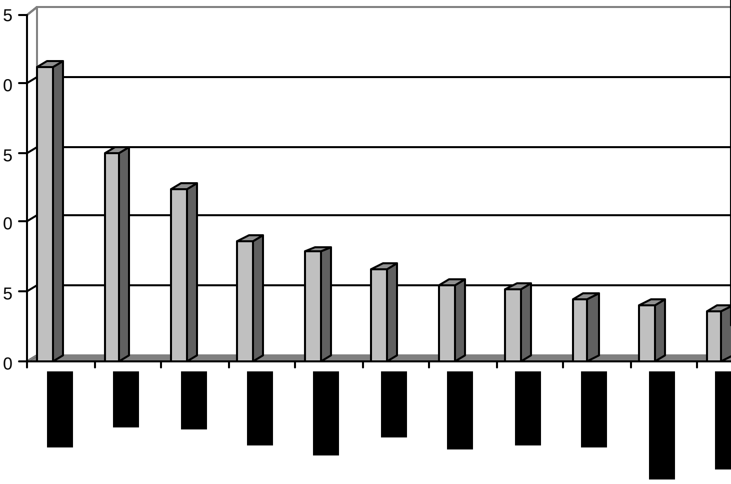

Figure 9: MOF Relative Value - Initiate and Carry Out Planning

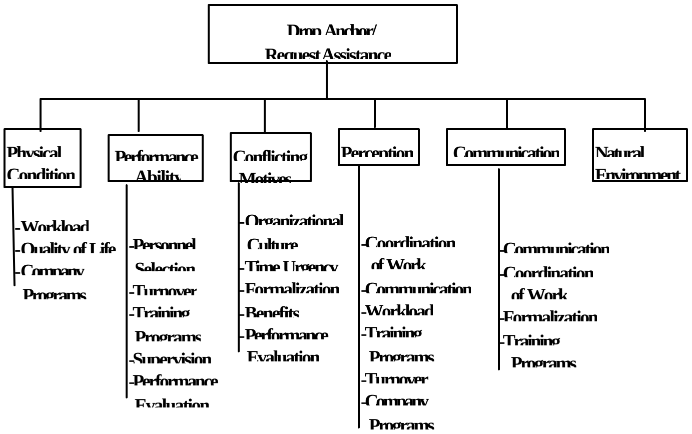

Figure 10: Factors Influencing the Decision to Drop Anchor/Request Assistance

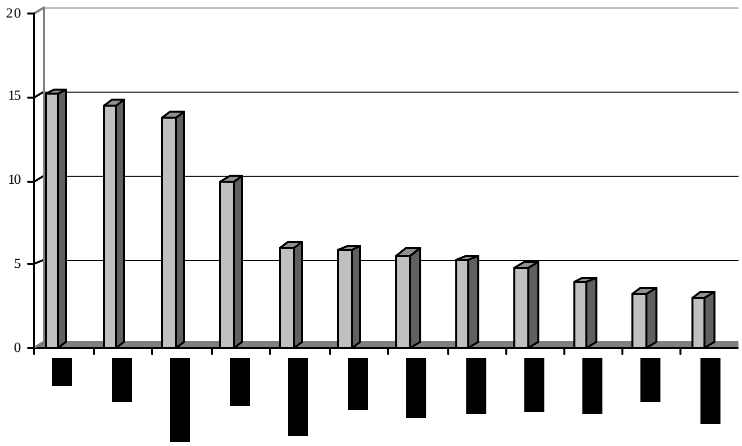

Figure 11: MOF Relative Value - Decision to Drop Anchor

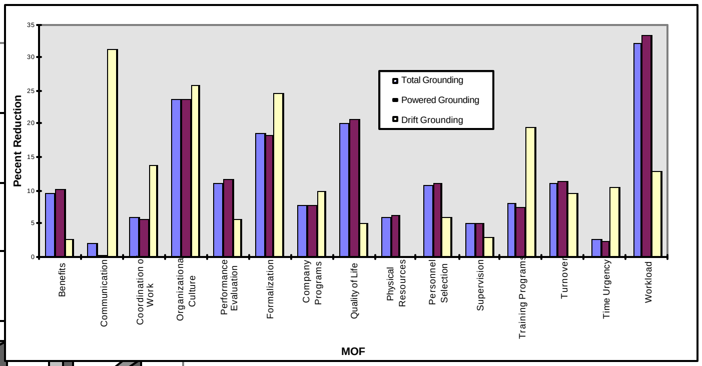

Figure 12: Reduction in Probability of Grounding for Inadequate Excellent MOF Change

The MO determined to have the largest influence on the probability of grounding are workload, organizational culture, quality of life, and formalization. Communication and training have a significant impact on Planning error. The MOFs having the largest impact on the powered grounding portion of the probability of grounding also dominate the total probability of grounding. This is due to the fact that powered grounding represents the largest contribution to the probability of grounding.

COMPARISON WITH ISM CODE FACTORS

The MOFs emphasized by the ISM Code were previously discussed. Table 2 compares a listing of MOFs determined to have the largest impact on grounding with factors emphasized by the ISM Code.

Table 2. Comparison of ISM and Important Model MOFs

ISM MOFs	Model Important MOFs
Organizational Culture	Workload
Safety Culture	Organizational Culture
Organizational Learning	Quality of Life
Formalization	Formalization
Coordination of Work	Performance Evaluation
Communication	Turnover
Personnel Selection	Personnel Selection
Training Process	Benefits

The ISM Code emphasizes both organizational culture and safety culture. In this analysis, safety culture was assumed to influence all other variables. The workload factor, determined to have the greatest influence on the probability of grounding, is not addressed in the ISM Code. Quality of life, benefits and crew turnover are also not explicit in ISM. Some of these differences may reflect the model's focus on tanker grounding vice the more general applicability of ISM, but clearly workload stands out as an important issue which should be addressed.

Workload or work hours are not explicitly addressed in any current IMO regulation. This must be corrected. OPA 90 limits the work hours for tanker officers to 15 hours in a 24 hour period or 36 hours in a 72 hour period. This makes it necessary for the Master and Chief Mate to delegate more routine duties such as cargo duties so that they are available on the bridge for critical transits. Regular uninterrupted sleep, stress, health, and pay practices which reward inefficient work also contribute to fatigue and the impact of a heavy workload. They are and must be considered under other MOFs such as formalization, coordination of work, company programs, supervision and time urgency.

CONCLUSION

The operation of oil tankers represents a significant risk to the environment due to the severe consequences of oil spills. Tankers are the largest contributor by vessel type to worldwide spill volume. One of the largest causes of accidents involving oil tankers is the event of grounding. The probability of grounding is largely influenced by the performance of the individuals responsible for the operation of the tanker. Management and organizational factors are critical to this performance. This research indicates that the probability of grounding can be reduced by over 99 percent when MOFs are implemented effectively. The ISM Code provides an important mechanism for achieving and sustaining this goal.

The MOFs determined to have the greatest impact on the probability of grounding are workload, organizational culture, quality of life, and formalization. Workload and work hours are not specifically addressed in current IMO regulation. This is an important issue which requires IMO attention.

This model provides a methodology to quantitatively assess the impact of MOFs in specific risk areas. It can be used to support investment strategies for tanker operations and in accident investigations.

Future work planned for this methodology includes the collection of more expert opinion, extension to collision and other safety issues, further sensitivity analysis, and the update of fault trees and error probabilities to reflect new technology and methods such as GPS and ECDIS.

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