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Full Length Research Paper

Human reliability analysis (HRA) emanating from use of technology for ships navigating within coastal area

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The traditional approach to the study of human factors in the maritime field involves the analysis of accidents without considering human factors reliability analysis. The main approach being use to analyze human errors are statistical approach and probability theory approach. Another suitable approach to the study of human factors in the maritime industry is the quasi-experimental field study where variations in performance (for example attention) can be observed as a function of natural variations in performance shaping factors. This paper analyzes result of modeling human error and human reliability emanating from the use of technology on board ship navigation in coastal water area by using qualitative and quantitative tools. Accident reports from marine department are used as empirical material for quantitative analysis. The literature on safety is based on common themes of accidents, the influence of human error resulting from technology usage design, accident report from MAIB and interventions information are use for qualitative assessment. Human reliability assessment involves analysis of accident in waterways, emanating from human-technology factors interface. This paper report an enhancement requirement of the methodological issues with previous research study, monitoring and deduce recommendations for technology modification of the human factors necessary to improve maritime safety performance. The result presented can contribute to rule making, and safety management leading for development of guideline and standards for human reliability risk management for ship navigating within inland and coastal waters.

Key words: human factors, human errors, maritime, accident, reliability analysis, safety, risk.

INTRODUCTION

Humans have relied on oceans, lakes, and rivers to ship goods from one end to another throughout the recorded history. Today, over 90% of the world's cargo is transported by merchant ships due to various reasons; including the fact that it is the cheapest form of transportation. The shipping industry has a fairly good safety record, however, maritime accidents have a high potential for catastrophes. Past experiences research report indicate that in the shipping industry around 80% of all accidents are rooted in human error (Fortland, 1996). Safety has been an immense public concern, especially caused in operations risk like: nuclear power generation, nuclear weapons, aviation, chemical/ petroleum processing and marine transportation (Robb et al., 1996).

There are several basic aspects of maritime activity that make it unique. Ships are complex, confined and isolated systems. They are sufficient on energy supply, they have a limited manpower and resources, and they have a limited response capacity to face emergencies. These particular characteristics made maritime trade a

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risky activity, where a fault in navigation or in usual port operations can leads to injuries or lost of life, to damage of property and sometimes irreparable damage to maritime environment (de la Campa Portela, 2005).

The main purpose of navigation is a safe and efficient sailing of the ship between diverse points which require steering the ship movement on a planned trajectory. The accident occurrence of factors affecting the ship's movement causes its limitation. The ship's sailing should be safe, so that it does not cause navigation accident. A navigational accident is an unwanted occurrence which can cause loss of life or health, loss or damage to ship or cargo, the pollution of natural environment, damage to the hydro-technological structure, and economical loss due to delay in the port and associated activities.

This paper presents the result of application of quantitative and empirical approach to analyze human factors for reliability assessment of ship navigating in coastal water. The approach is based upon a theoretical framework of well-known models. It is possible to benefit from the causal connection between human errors and accidents. It is possible to get a fast and easy access to empirical material from historical data that are analyzed, compared to field studies or laboratory studies. The use of modest approach to standardized developments process through qualitative and quantitative risk assessment and analysis methods is necessary for human reliability analysis (HRA) to perform. Quantitative risk assessment and analysis for HRA are best analyzed using failure modes and effects analysis (FMEA), fault tree analysis (FTA) and event tree analysis (ETA). Computer Relex reliability software is use for quantitative risk. While for the qualitative risk assessment and analysis method, some checklists and safety or review audits is emphasized.

LITERATURE REVIEW

Human factors deal with human abilities and limitations in relation to the design of systems, organizations, tools etc. Important parameters are safety, efficiency and comfort. Human errors and human factors are often studied separately; therefore, the relationship between them is often overlooked. According to Gordon et al. (1998), proposes a framework for describing the relationships between underlying human factors and more immediately evident human errors. Gordon categorizes human factors as individual, group, or organizational, following the Rasmussen model "Perceptions on the concept of human error," that categorize human errors as skills-based, rule-based, or knowledge-based.

System-induced errors reflect deficiencies in the way the total system is designed. They include mistakes in designating the numbers and types of personnel, in training, in data resources, in logistics and in maintenance requirements and support. Design-induced errors result from inadequacies in the design of individual items of equipment. The new equipment characteristics create special difficulties for the operator which substantially increases the potential for error. Operator-induced errors can be traced directly to an incompetency on the part of the individual who makes that error. They include errors resulting from lack of capability, training, skill, motivation, or from fatigue.

Several studies and case reviews have found that organizational factors may be the most critical in considering human factors contributions to marine accidents. At the organizational level, various factors may contribute to an increase in incidents and accidents, including cost-cutting programs and the level of communication between work-sites (Gordon, 1998).

According to the US Coast Guard's (USCG) risk-based decision-making guidelines categorize human error into four categories, which form a matrix: intentional errors, unintentional errors, errors of omission and errors of commission. An unintentional error is an act committed or omitted accidentally, with no prior thought; therefore, intentional errors have also been referred to as "routine violations". An error of omission occurs when an operator fails to perform a step or task. An error of commission occurs when an operator performs a step or task incorrectly (USCG, 2006). Maritime transportation is a complex socio-technical system formed by four interdependent factors as technology, environment, people and organizational structures. Each of these dimensions has direct or indirect effects on maritime casualties, but failures of human action and judgment have often been seen as an important part of the causes. Main cause of growing number of accidents has been attributed specifically to "human error".

Nivolianitou et al. (2006) pointed out those technical factors that are more readily resolved than human factors through technological and regulatory "fixes" leaving human-related errors and breakdowns as the most probable cause of industrial accidents (Hee et al., 1999). Supporting this theory, noting structural or technological failures are generally responsible for less than 20% of accidents involving complex systems, and noting this is "a tribute to technology".

By comparison, more than 80% of accidents can be attributed to the "unanticipated actions of people" leading to undesirable outcomes. Hee et al. (1999) concluded that human inputs to technolo-gical and engineering processes may actually contribute to accident risks from the beginning stages of equipment design.

There are many methods and techniques that have been developed to perform various types of analysis, in areas such as reliability and safety. Several different accident forecasting models and analytical tools have been developed in an attempt to identify root cause errors in human systems and develop preventive measures that intervene at the appropriate level, although the proper categorization of human and organizational errors is critical to this process (Nivolianitou et al., 2006). Quantitative analysis relies on statistical methods and databases that identify the probability and consequence. This objective approach examines the system in greater detail for risk (Robb et al., 1996).

Quantitative risk analysis generally provides a more uniform understanding among different individuals, but requires quality data for accurate results. Qualitative risk analysis uses expert opinion to evaluate the probability and consequence. This subjective approach may be sufficient to assess the risk of a marine system (Robb et al., 1996).

The qualitative method for risk assessment or analysis is designed for the purpose of enhancing one's awareness of potential problems and can assist one in analyzing these risks. A combination of both qualitative and quantitative risk analysis can be used depending on the situation.

FMEA is another powerful tool used by system safety and reliability engineers/analysts to identify critical parts, functions and components whose failure will lead to undesirable outcomes such as production loss, injury or even an accident.

The tool was first proposed by National Aeronautics and Space Administration (NASA) in year 1963 for their obvious reliability requirements. Since then, it has been extensively used as a powerful technique for system safety and reliability analysis of products and processes in wide range of industries - particularly aerospace, nuclear, automotive and medical.

The concept of fault tree analysis was originated by Bell Telephone Laboratories as a technique to perform a safety evaluation of the minuteman launch control system. Bell engineers discovered that the method used to describe the flow of "correct" logic in data processing equipment could also be used for analyzing the "false" logic which results from component failures. A FTA is useful for understanding the mode of occurrence of an accident logically. Furthermore, given the failure probabilities of system components, the occurrence probability of the top event (TE) can be obtained. Traditionally, it is usually assumed that the basic events within a fault tree are independent of each other and could be represented in terms of probabilistic numbers. With this assumption, quantitative analyses of fault trees are usually performed by considering two cases: (1) fault trees without repeated event, and (2) fault trees with repeated events.

Event tree analysis is a binary form of a decision tree for evaluating the various multiple decision paths in a given problem. ETA appears to have been developed during the WASH-1400 nuclear power plant safety study. The WASH-1400 team realized that a nuclear power plant PRA could be achieved by FTA; however, the resulting fault trees (FTs) would be very large and cumbersome, and they therefore established ETA to condense the analysis into a more manageable picture, while still utilizing FTA.

Human error and accident in waterways

The 21st century shipping industry faces new challenges in term of accident and its consequence. For instance, 25 years ago the average cargo ship would have been manned with a crew of between 40 and 50 (Grech et al., 2002). Today technological advances have contributed to decrease manning, in some cases to just 22 seafarers on a very large crude carrier (VLCC). There are two sides to the technological advances. Improvements in ship design and navigation aids have reduced the frequency and severity of shipping incidents. In turn, the reduction of failures in technology has revealed the underlying level of influence of human error in accident causation (Catherine, 2006).

The fact that human factors contribute to accidents is generally accepted, but there is no consensus on the importance of this factor. Suggestions regarding the proportion of marine accidents caused by human errors vary from 50 to 90% of the total (Kletz, 1991). The main causes of accidents is shown in Figure 1 where first 60% of the total number of claims recorded that human error was the direct cause and further 30% human error is from indirect contributory cause.

Human factors are based on the acknowledgement that human characteristics and behaviors are intrinsically linked with the functioning of the technology, people, design, building, maintains area and operation. The human-technology relationship works in both directions. Not only do humans impact the functioning of our technology, but technology can also influence human decisions and actions. Since human factors is triggered by human errors, which are the main source of risk in maritime activities, it seems interesting to develop methodologies that allow evaluating quantitatively and qualitatively the real incidence of several human factors over maritime accidents happening with the aim of taking human factors into account in properly developed risk management plans (de la Campa Portela, 2005).

Human reliability assessment required system based approach analysis that makes it easy to determine human factors risk levels through statistical analysis of maritime accidents. The risk of disasters cannot be eliminated, but risks can be reduced by establishing better safety criteria prior to an accident. This paper present the finding of human reliability analysis that can reduce the probability risk in ship navigation in coastal area by considering the relationship between the human factors and technologies, the cause of the accident from technological influence to human error and deduce solution from the analysis (Ayyub, 2002).

METHODOLOGY

In this study, few qualitative and quantitative approach methods were used to analyze the relationship between human factors and technologies following the analysis of the causes of accidents from

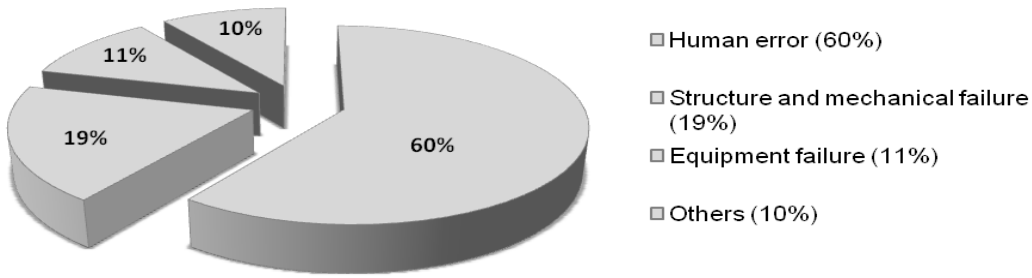

Figure 1. Main causes of accidents (Marine department, Malaysia, 2009).

technological influence to associated human error and in deducing the solution from the analysis. The methods used include application of the checklists (Failure Modes and FMEA, FTA) and ETA.

Checklists

This is a qualitative approach to ensure that the organizations are complying with standard practices. The checklists can be used as a preparation for a port call to avoid unnecessary problems and delays. The checklists may be included in the International Safety Management (ISM) procedures as documentation to checks for maintenance etc. The list can be filled in manually or printout or electronically. The list is qualitatively assessed in correlation between human and technology, and management for operation of ships. Checklist is observed to capture the gaps in the system.

FMEA

FMEA is a systematic tool for identifying the effects or consequences of a potential product or process failure; and the methods to eliminate or reduce the chance of a failure of occurring. It involves identification of the process functions that has been clearly articulated. It requires preparation of a failure mode analysis and preparation of worksheets by using reliability analysis software, like Relex or isograph. And next, is identification of the failure modes and the description of the effects of these failure modes. This is followed by establishment of a numerical ranking for the severity of the effect in order to identify the cause of each failure mode. The occurrence factor and the likelihood of detection are determined. The risk priority numbers (RPN) is determined by a product of the numerical values of severity, occurrence and detection ratings:

RPN = (Severity) x (Probability) x (Detection)

Finally, recommendation of action(s) to address potential failures that have a high RPN can be made.

FTA

Fault tree analysis is generally performed graphically using a logical structure of AND and OR gates. There should be only one top event, and all risk contributing factors must tree down from it. Actual number of failure probabilities, area assigned to the contributing factor. Traditionally, it is usually assumed that the basic events within a fault tree are independent of each other and could be represented in terms of probabilistic numbers. There are five steps involved for the basic Relex FTA, which are to define the undesired event to study. Next, is obtain an understanding of the system. Next is to only construct the fault tree and evaluate it. Lastly, controls for the hazards are identified.

ETA

Event tree analysis is based on discrete binary logic, in which an event is in either ON or OFF state which indicate that failure did not happen, failure happened or a component of it has not failed. It is valuable in analyzing the consequences arising from a failure or undesired event. An event tree begins with an initiating event of interest. The consequences of the event are followed through a series of possible paths. Each path is assigned a probability of occurrence and the probability of the various possible outcomes can be calculated from them.

Technique of human error probability (THERP)

Accident data

Casualty statistics: The total losses of all ships and boats during the years 2000 to 2009 are 289 in number, according to the Malaysian Marine Department data that reported to Port Klang's Vessel Traffic Management System (VTMS) for annual casualty statistics in Peninsular Malaysia, which include coastal areas of Peninsular Malaysia and the Straits of Malacca. Total losses in number during the years of 2000 to 2009 are presented in Figure 3 and 4 respectively. Sinking or foundering accounts for total losses of almost 50% of accident compared to collision which accounts for total losses amounting to only 26.30 % as shown in Figure 2.

Figure 3 and 4 shows that the total accident of ships and boats in Malaysia coastal areas and the Straits of Malacca from year 2000 till year 2009 respectively. From Figure 3, analysis shows that the highest ranking of accident which only occurred in average of eight cases at the Malaysia coastal areas in ten years. From 2000 until 2009, a total of 215 accidents including sinking or foundering, collision, fire or explosion and grounding occurred in the Straits of Malacca with an average of 30 accidents per year. About 353 vessels of all types passes through the Straits of Malacca each year and 35% of them are oil tankers and this has potential to increase the discharges of oil in the sea including ballast water, oil, sewage and others solid wastes. As shown from the bar chart, the probability of an accident to occur at the Straits of Malacca is high if compared to the Malaysia coastal areas. This is because Malacca Straits is a golden heritage of the littoral states such as Malaysia, Singapore and Indonesia. It is not only rich in marine resources but is also one of the oldest and busiest shipping lanes in the world.

As the years come by, from year 2004 till 2009, there were reducing numbers in maritime casualties which in average of ten accidents per year. In accordance with the International Maritime

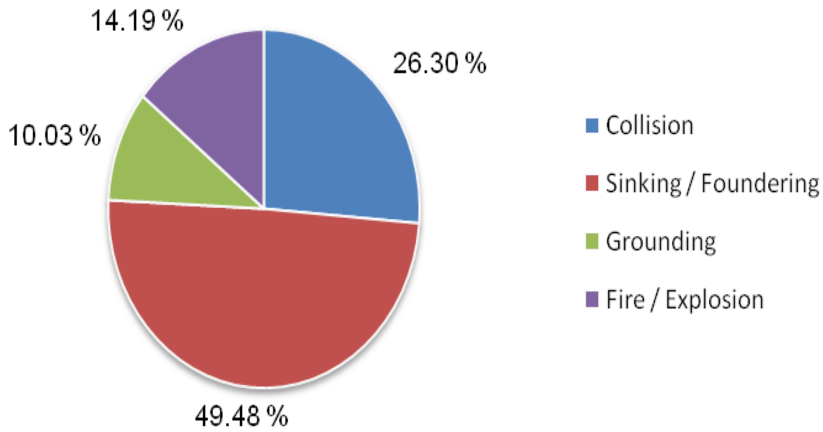

Figure 2. Total losses of ships in number during the Years 2000 to 2009.

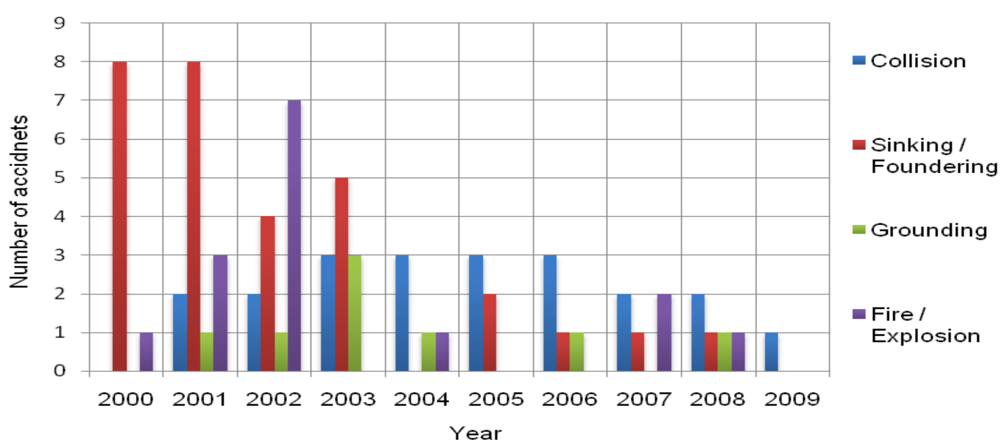

Figure 3. Total of accident of ships and boats at Malaysia coastal areas from Years 2000 to 2009.

Organization's (IMO) Rules for vessels navigating through the Straits of Malacca, an under keel clearance of 3.5 m is required for shipping safety of navigation and reduction in the risk for an accident to occur.

RESULTS AND DISCUSSION

Qualitative risk assessment and analysis method

Checklists

Prior to arrival and departure of vessel in port, checks on operation procedure should be carried out after long ocean passages and before entering restricted coastal areas. The incident command system (ICS) emergency checklist for collision is carried out, actions include switch the VHF to Chanel 16, check for the watch alarm system etc. In the navigational watch checklist, the primary duties of the Officer of the Watch (OOW) are watch keeping, navigation and GMDSS radio watch keeping complying all times with the COLREGS and STCW95. The Officer of the Watch is not allowed to leave the bridge until properly relieved. While in the sole lookout checklist, a sole look-out is allowed only during day light according to the STCW code. The qualitative exercise is matched closely with guideline given by reference IMO (2002) and FortLand (2004).

The master, before allowing the exercise, has to carefully assess the situation and ensure that it is safe to operate with a sole lookout of the state of weather, visibility and traffic density. In addition, basically radar also should be kept running and fully operational at all times. The log books checklist which includes a correct record of the movements and activities of the vessel should be kept in the appropriate log book during the watch. Instructions for the completion of log books should be strictly observed as per respective national regulations and rules. Navigational and radio equipment has to be checked periodically to ensure satisfactory and safe operation.

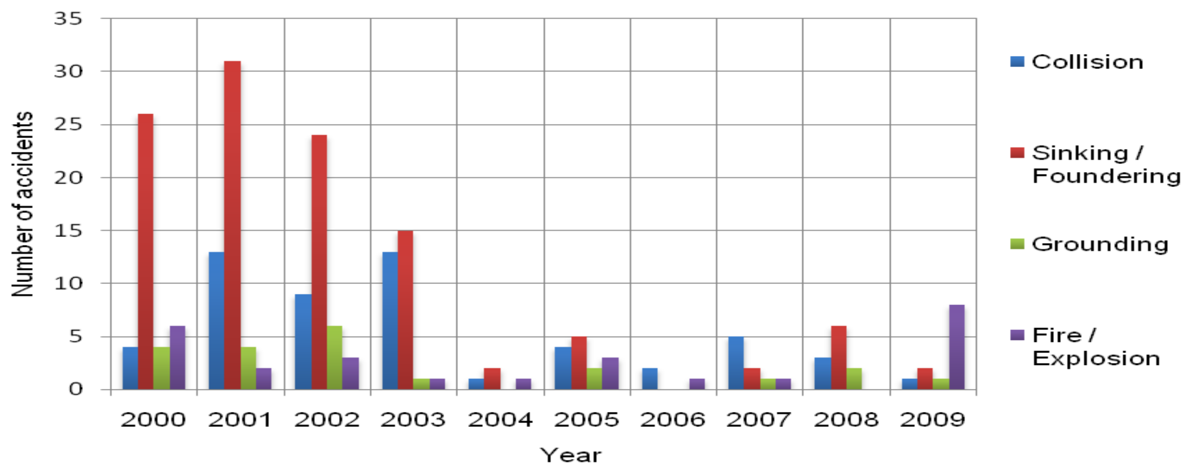

Figure 4. Total of accident of ships and boats at Malacca straits from Years 2000 to 2009 (Source: Malaysian Marine Department).

Quantitative risk assessment and analysis method

Failure modes and FMEA

Analysis is carried out by using Relex FMEA. The following is the Relex FMEA worksheet (Figure 5) based on the process: water leaking into vessel. The potential failure modes for the sinking or foundering process includes the failure system of bilge alarm, inadequate of watertight bulkhead, failure of seawater pipe work and the perforation of hull plating. One of the causes to the failure of the bilge alarm system is the electrical failure where the terminal connector block is not suitable for used and the screw terminals provide an opportunity for corrosion resulting in the connection failing. Other than that, as previously mentioned, human factor play a main role, it is also possible that a bilge level alarm that activates every time, vessel motion will be ignored or turned off.

As a result, the RPN is established as well. The graph of FMEA risk level (Figure 6) is to view a graph of the failure modes with the highest RPN values. In the graph that is obtained, the highest RPN is 252 for seawater pipe work failure. The pipe failure which led to the flooding was caused by simple sea water corrosion. Piping failures are so far from the main cause of all fishing vessel flooding and foundering, where the cause has been identified. While for the potential failure modes like bilge alarm system failure and perforation of hull plating has RPN, 216 and 192 respectively. Steel hull plating failures occur frequently. Failure mode of lack of watertight bulkhead has its RPN at 168 where the severity ranks at 7 and occurrence ranking at 6. To have a watertight machinery compartment, the maintenance and inspection of the watertight integrity must be adequate. The outcome of risk outcome is measure using guideline provided by reference (USCG, 2006).

FTA

From accident data, it has been identified that sinking or foundering accident has the highest ranking among the other accidents. Thus, it means that a systematic approach must be undertaken to identify all possible causes and their consequences, so that risk can be reduced to a minimum level through appropriate safety measures. By using the fault tree symbols, a simple fault tree for a top event, water leaking into vessel, is shown in Figure 7. The occurrence probability of the top event of a fault tree can be calculated when the probabilities of the occurrence of basic fault events are known. This can only be obtained by first calculating the occurrence probability of the resultant (that is, output) fault events of intermediate by using lower logic gates such as AND and OR.

Thus, the probability of occurrence of the number of AND gate output fault event is expressed by:

$$P(x_0) = \prod_{i=1}^{n} P(x_i) \qquad (1)$$

Where, $P(x_0)$, is the probability of occurrence of the AND gate output fault event x_0; n, is the number of AND gate input fault events; $P(x_i)$, is the occurrence probability of AND gate input fault event x_i; for i = 1, 2, 3, …., n.

Similarly, the probability of occurrence of the OR gate output fault event is given by:

$$P(y_0) = 1 - \prod_{i=1}^{k} \{1 - P(y_i)\}$$

Relex

POTENTIAL
FAILURE MODE AND EFFECTS ANALYSIS
(PROCESS FMEA)

Name:
Process Responsibility:
Key Date:
Core Team:

FMEA Identifier: FMEA2
Page 1 of 1
Prepared By:
FMEA Date (Orig.) (Rev.) 3/1/2010

Process Function / Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/ Mechanisms of Failure	Occur	Current Design Controls Prevention	Current Design Controls Detection	Detec	R.P.N.	Recommended Actions	Responsibility & Target Completion Date	Action Results: Actions Taken	Sev	Occ	Det	R.P.N.
Sinking / Foundering Water leaking into vessel	Perforation of the hull plating	Hull plating cracked	8			6			4	192	Periodically using ultrasonic thickness measurements			8	5	4	160
	Bilge alarm system failure	Undetectable	9		Electrical faillure	6			4	216	Regular manual checks			9	5	4	180
			9		Lack of inspection and maintenance	6			4	216	It should be tested before sailing			9	5	4	180
	Seawater pipework failure	Fatigue cracks	9		Loose fittings	7			4	252	Periodically inspected internally of pipework			9	6	4	216
			9		Pipework corrosion / erosion	7			4	252				9	6	4	216
	Lack of watertight bulkhead	Watertight integrity inadequate	7			6			4	168	Maintenance and inspection of watertight integrity carry out frequently			7	5	4	140

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Figure 5. A Relex FMEA worksheet which based on the process: water leaking into vessel.

Where, $P(y_0)$, is the probability of occurrence of the OR gate output fault event y_0; *k*, is the number of OR gate input fault events; $P(y_i)$, is the occurrence probability of OR gate input fault tree event y_i; for i = 1, 2, 3, …., k.

By substituting the given probabilities and calculated values of the top event: Water leaking into vessel into the equations. Thus, the probability of occurrence of the top event: water leaking into vessel is 0.1759.

In this regard, better training and procedures can help to promote better communications and coordination on and between vessels. Poor equipment design was a causal factor in one-third of major marine casualties. A proper consideration by equipment designers to factors such as how a given piece of equipment will support the mariner's tasks and how it can be integrate into the entire equipment "suite" used by the mariner can be a very helpful step. The issue of "inexperience, lack of knowledge and training" is concerned with poor understanding of mariners of how automation works or under what conditions it was designed to work effectively. Consequently, mariners sometimes commit errors in using the equipment. Poor inspection and maintenance is another important issue because poor maintenance of navigational equipments can lead to dangerous work environments and lack of backup systems that need to carry out emergency repairs.

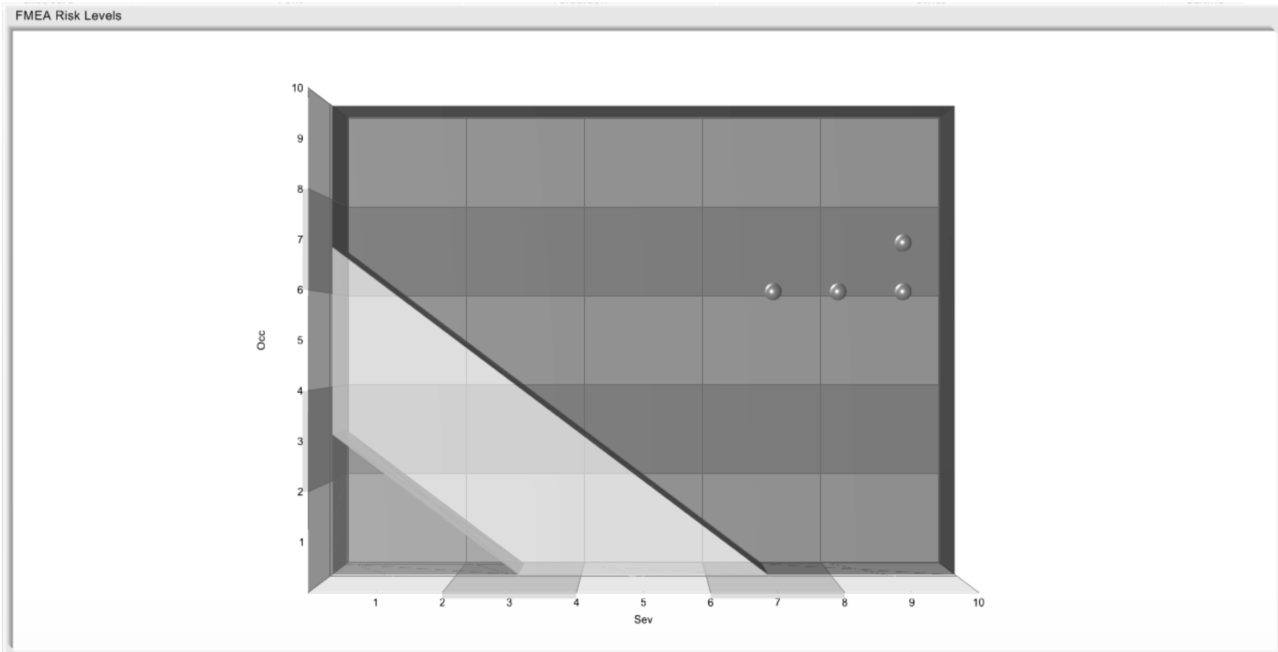

Figure 6. A FMEA risk level based on the process: water leaking into vessel.

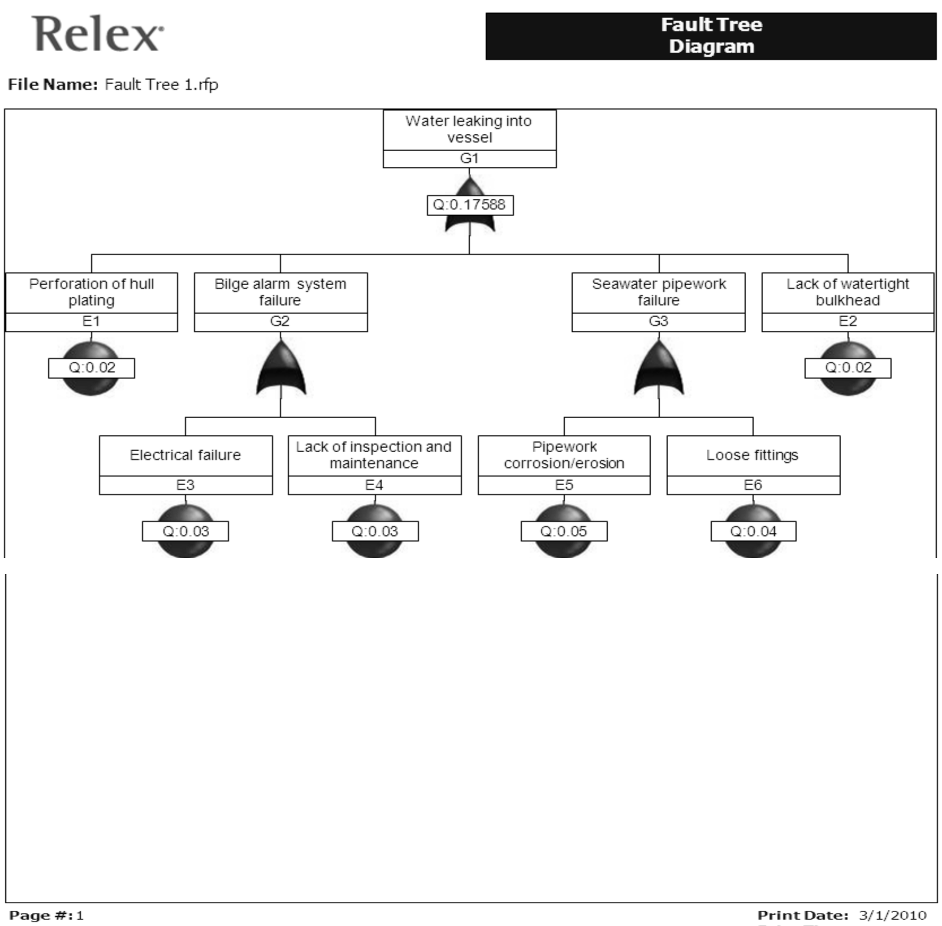

Figure 7. A fault tree diagram for the top event: water leaking into vessel.

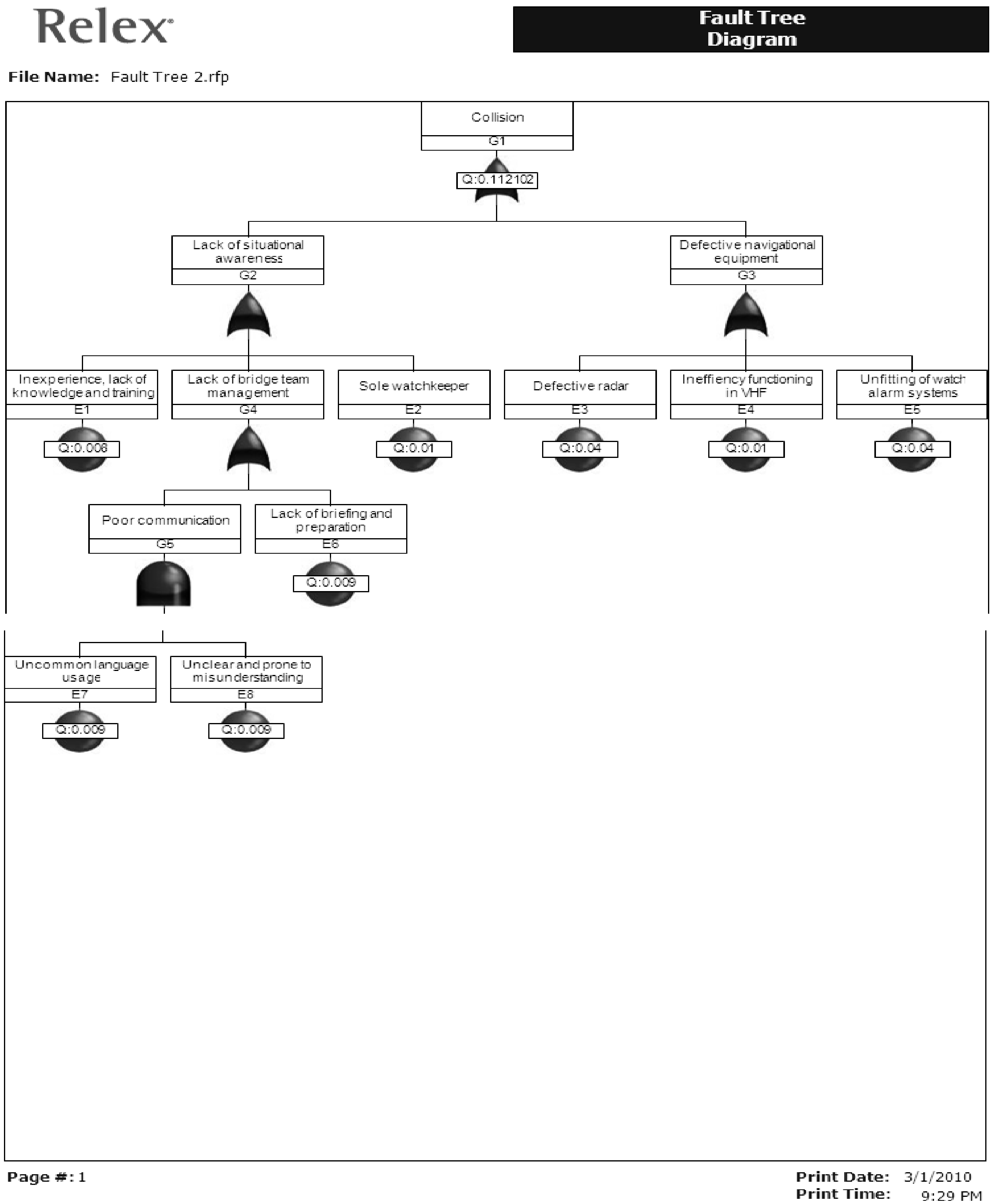

Figure 8. A fault tree diagram for the top event: collision.

After the first top event, fault tree analysis is repeated for the second top event: collision. Fault tree for a top event analysis by RELEX Reliability software, collision, is shown in Figure 8. Also by substituting with manual calculation the given probabilities and calculated values of the top event: collision into the equations. Thus, the

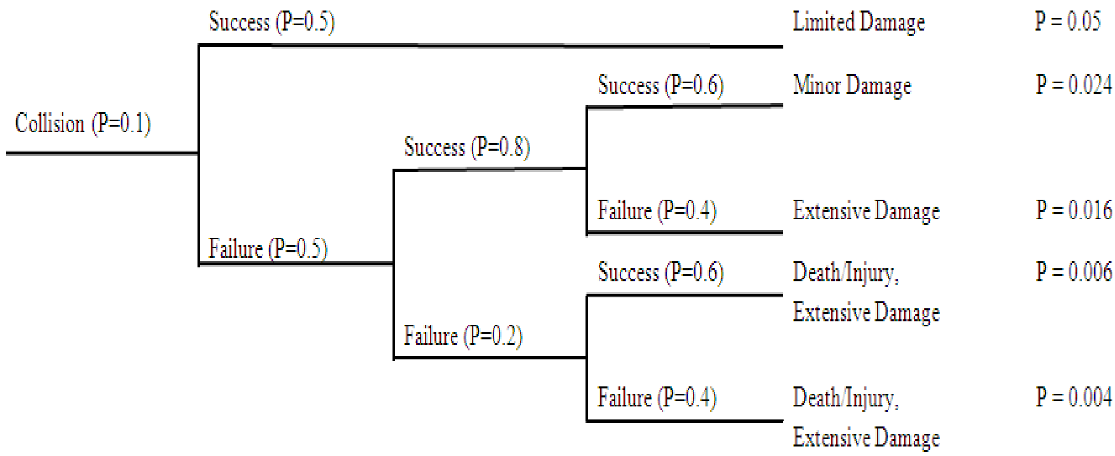

Figure 9. Event tree analysis for collision.

probability of occurrence of the top event: collision is 0.1121 (ETA, 2001).

ETA

The goal of ETA is to determine the probability of all the possible outcomes resulting from the occurrence of an IE. By analyzing all possible outcomes, it is possible to determine the percentage of outcomes that lead to the desired result and the percentage of outcomes that lead to the undesired result. Each safety design method is evaluated for the contributing event:

(a) Operates successfully
(b) Fails to operate

Each success/failure event is assigned a probability of occurrence, and the final outcome probability is the product of the event probabilities along a particular path. When computing the success/fail probability for each contributing PE, the PE states must always be sum to 1.0, based on the reliability formula that:

$$P_{SUCCESS} + P_{FAILURE} = 1$$

Conclusion

There are errors (both human and technology) common to accidents in waterways. Employing methods through which these can be moderated and reduced could potentially enhance shipping safety. The practical application of human reliability analysis is clear. It requires obtaining the cause parameters, both direct and indirect parameters, from the studied factor. The parameters that help to better understand the root of the presence of such a factor, and help to take punctual, specific and direct corrective actions to try to minimize the accident risk. The use of systemic HRA with right data, assessment and analysis can be is one mainstay to accident reduce, control and prevent maritime accident and sub sequential improvement of maritime safety. Nowadays, it has becomes a very important tool to identify the problems related to human factor. Technological and engineering improvements in the marine sector have shown in some cases, to increase the risk of an accident occurring due to human factors. The human factor accidents are mostly caused by lack of skill or knowledge, or other risk compensation.

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