

Survivability of Ships at Sea: A Human Factors Perspective

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Abstract - Most fatal accidents at sea were caused by small incidents that escalated into uncontrolled severe events. This research is trying to develop a model to calculate the probability of fatal accidents, given a critical incident has already occurred. The focus of the study is on the human factors. Hardware reliability perspective is adopted. The vessel is considered as a system to be protected by several barriers. The crew are modelled as the active barriers and distinguished into different functions: to perceive, decide and act. Markov diagram is utilized to model different situations on the vessel. A mathematical model to calculate the probability of failure on emergency is formulated. A new parameter is defined showing the survivability of a vessel, given a critical incident took place.

Keywords

survivability, emergency situation, human factors, probability of failure on emergency, ship operation, Markov model, safety instrumented system

INTRODUCTION

Perrow (1999) describes marine accidents as a fascinating country. He illustrates marine system as an “error-inducing” system, a system which the configuration of its components induces errors and defeats attempts to reduce error.

Rumawas & Asbjørnslett (2010) documented fatal ferry accidents at sea which occurred every year in developing countries due to extreme conditions. Low operating standards, cheap fares, mixture of cargo and passengers, low safety awareness, inadequate regulations, inadequate vessels, second-hand fleet, overcrowding and overloaded are the overall conditions of passenger ferries in developing countries (Spouge, 1991, Lawson & Weisbrod, 2005). According to Perrow, not a single failure is responsible for an error-inducing system. Accidents

are quite rare for any single ship. Marine system is moderately coupled. Even though failures occur continuously, recovery is possible because time constraints are not tight.

In the case of ferry accidents that were presented by Spouge (1991) and Lawson & Weisbrod (2005), recovery failed to take place when constraints become stricter because of the extreme condition.

Gardenier (1981) states that vessels continue to have problems of system failure detection and diagnosis. In open, unrestricted waters, the ship navigation system is tolerant to errors and other failures. As ships approach narrow, restricted channels and increasing traffic densities, the system's failure tolerance decreases.

The purpose of this article is to develop a model to predict the probability of the human operator restore the ship given an emergency situation has taken place. System reliability perspective will be adopted. Human elements will be treated as the barrier.

METHODS FOR RISK ANALYSIS AND MANAGEMENT

There are many methods and techniques to analyze risk which can be applied in marine systems (Ayyub et al, 2002, Kristiansen, 2005, Dhillon, 2007, Vinnem, 2007). Both qualitative and quantitative approaches are covered, including: what-if analysis, hazard and operability study (HAZOP), probabilistic risk analysis (PRA), failure modes effects and critically effect analysis (FMECA), bow-tie model which includes fault tree analysis and event tree analysis. International Maritime Organization (IMO) published formal safety assessment (FSA) guidelines for assessing the risks relating to maritime safety and the protection of the marine environment (IMO, 2002).

Human reliability analysis

There are a lot of methods available to conduct human reliability analysis to date. Gertman & Blackman (1994) documented 38 methods, Hollnagel (1998) identified 35-40 HRA approaches, while Stanton et al (2000) reviewed over 200 HF methods and techniques, and documented more than 90 design and evaluation methods. Several methods which are considered relevant and potential to be applied on ships operations are presented as follow:

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Accident Investigation and Progression Analysis (AIPA)
 AIPA is a method to assess the probability of an operator to carry out a certain response for a given time. The method was developed in 1975 by Fleming et al (Hollnagel, 1998). Expert judgements were utilized to estimate probabilities of actions. The operator was seen as a black box in this model.

Operator Action Tree (OAT)

The OAT was developed for modelling cognitive errors by nuclear-power-plant operators during accident conditions (Wreathall, 1984). It is based on the assumption that the response of an event can be separated into three stages: (1) observing or noting the event, (2) diagnosing or thinking about it, and (3) responding to it (Hollnagel, 1998). OAT focuses the probability of failure in diagnosing an event.

Technique for Human Error Rate Prediction (THERP)

Swain & Guttman (1983) developed one of the most widely used HRA methods to predict human error probabilities (HEP) and to evaluate the degradation of a man-machine system in nuclear power plants. The method relies heavily on task analysis which discriminates human performance into three different behavioural elements: (1) sensory signals and related perceptions, (2) information processing, decision-making and other mental processes, and (3) the required responses. In THERP, the basic HEP is acquired for a standard condition and then adjusted for other conditions by considering some performance shaping factors (PSFs). The human performance, which is decomposed into tasks, is represented by an event tree. Each task can be performed successfully or unsuccessfully. Recovery mechanism for unsuccessful task is acknowledged in THERP.

Systematic Human Action Reliability Procedure (SHARP)
 SHARP is used for the systematic human reliability assessment to predict the probability that a nuclear control room operator will respond to a plant event within a given time. The approach is developed based on human cognitive reliability and the operator action model (Spurgin et al, 1987).

Markov method

Dhillon (1982, 2003) proposed Markov method to be used in performing human reliability analysis (see Fig 1). Assumed that an operator is conducting his tasks in changing environments: normal and abnormal. The transition rate from normal to abnormal environment is defined as α_n , while the opposite is α_a . Human error rate from state 0, the operator performing task correctly in normal environmental condition, to state 2 is defined as λ_h . In abnormal environmental condition, the human error rate from state 1 is defined as λ_{ah} . Parameters of interest in this Markov model include the probability of human committed error as the

function of time t , $P_2(t)$ and $P_3(t)$, and the mean time to reach the worst state, called mean time to human error (MTTHE). Detail solutions of those parameters can be found in Dhillon (2003).

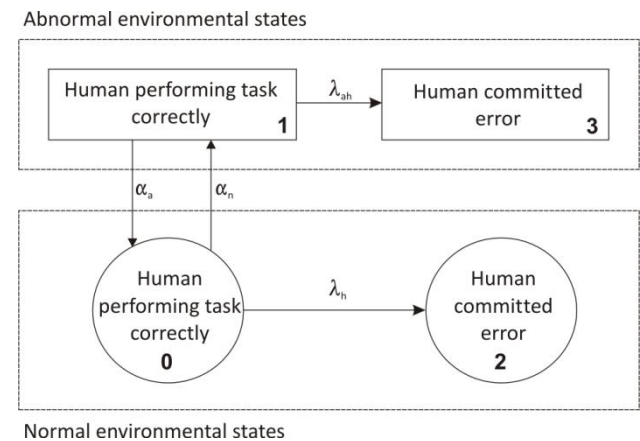


Figure 1. System state space diagram (Dhillon, 2003)

Accident model and analysis

There are several methods developed to explain accidents at sea by considering the human and organization factors. Paté-Cornell (1993) used a probabilistic risk analysis (PRA) framework to analyze Piper Alpha accident. Kristiansen et al (1999) proposed a new methodology for marine casualty analysis by taking into account human and organizational factors. Hee et al (1999) developed Safety Management Assessment System (SMAS) to assess marine system from the human and organization factors perspective.

Safety instrumented system (SIS)

In the field of system reliability engineering, safety instrumented system (SIS) is defined as an independent protection layer that is installed to mitigate the risk associated with the operation of a specified hazardous system (Rausand & Høyland, 2004). The SIS comprises of sensors, logic solvers, and actuators (see Fig 2). Most of the time, the system is passive until a hazard, which is called a demand, occurs.

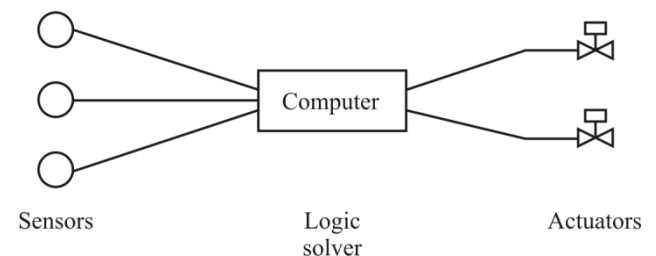


Figure 2. Safety instrumented system (SIS)

SIS has been applied widely in various industries, for instance the airbag systems in automotive industry and blowout preventer system in petroleum industry.

It is important that the SIS is working when a hazard comes. The probability that an element fails to work

when a demand occurs at $t = t_1$ is called the probability of failure on demand (PFD) (see Fig 3).

The average PFD of an element is determined by its failure rate (λ) and the test interval (τ , in hours). The average PFD for a single element is defined as (Rausand & Høyland, 2004):

$$PFD_{1001} = \frac{1}{2} \lambda \tau \quad (1)$$

assumed $\lambda\tau$ is small.

The total PFD for the system is defined as (BS, 2002):

$$PFD_{SYS} = PFD_S + PFD_L + PFD_A \quad (2)$$

where PFD_{SYS} is the average PFD of the SIS, PFD_S is the average PFD of the sensors subsystem, PFD_L is the average PFD of the logic subsystem, and PFD_A is the average PFD of the actuators subsystem. Assumed all numbers are small.

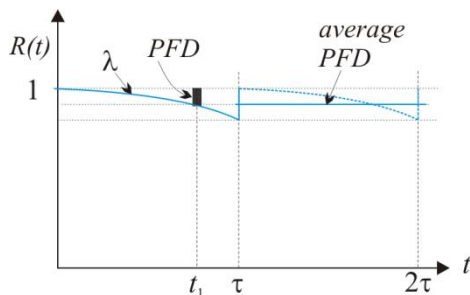


Figure 3. Probability of failure on demand

SYSTEM DESCRIPTION

Most vessels must operate all year around. Some ships follow a fixed route and schedule, while others are more random. Some ships may sail within several minutes, while others may sail for weeks. Some ships can be operated by one or two personnel, while others need more than fifty. Weather conditions and the vessels' conditions may vary from time to time. During normal conditions, most vessels can operate without any significant problem. It is assumed that a ship might experience an unfavourable condition, such as storm, blackout, critical system failure, or fire. These abnormal situations can escalate to a severe incident, unless the crew onboard detect the problem in time and know how to handle the situation properly.

Survivability of ships

Survivability of ships from the human factors perspective is defined as the probability that the crew can manage emergency situations, given some critical hazard has occurred. The crew must be able to perform the following functions: (1) sensing the hazard, (2) analyzing the situation and making the proper decision, and (3) conducting the right action. All these functions can be performed by one person or can be distributed among several crew members.

The types of accidents cover: collision, contact, grounding, stranding, foundering, capsizes, fire and explosion. Each accident category has its own scenario and potential hazardous elements which the crew must familiar with.

SIS model of the human element

The SIS framework is applied to model situations on a ship. The human element is regarded as the SIS and the vessel as the system to be protected. Hazard is taken as the demand.

Figure 4 shows an example of SIS model which consists of human element on a bridge operation. The people on the bridge act as sensors. They must observe the situation surrounding the vessel, the seaway, the sea state, navigational signs and all the necessary displays. In many cases, should there be any deviations, the crew will directly take some necessary actions, e.g., by adjusting a lever, push some buttons or turn a knob. In more serious cases, the situation must be reported to a higher rank officer before decisions are made and executed. Hazard may present without detectable. This situation is called latent phase or latent failure.

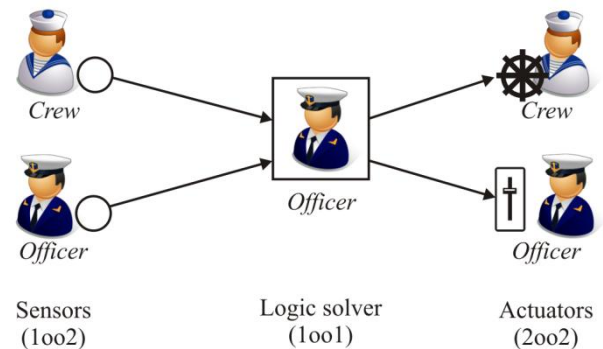


Figure 4. Crew modelled as SIS in bridge operations

Similar situations occur in other departments on board. The crew in the engine room must check all the necessary equipment and supplies through many visual and auditory indicators. The crew on the deck must monitor the conditions of the cargo, the passengers, etc.

Sensors work as a parallel system or one-out-of-two (1002) system; only one is required to function. Actuators work as a serial system or two-out-of-two (2002) system; both of them must work properly to keep the system's integrity. The logic server works as a single element, one-out-of-one (1001).

Comparable to the PFD in hardware reliability perspective, the probability of failure on emergency (PFE) is defined here.

Unlike hardware element which is considered to work well when it is new, the human element is the opposite. When a crew is recruited and placed on a vessel, he or she is not completely prepared for the

job. The crew is assumed to hold a certain level of knowledge and competence based his or her previous education, training and experience. However, every vessel is unique. Some orientation and adjustment will be required. On top, training will increase the capability of the crew significantly.

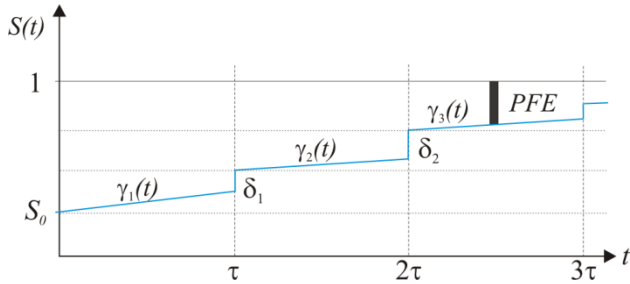


Figure 5. Probability of failure on emergency (PFE) and survivability

Survivability, $S(t)$ is determined as the function of previous knowledge (S_0), orientation, adaptation and on-the-job learning processes (γ) and formal training or assessment (δ).

$$S(t) = S_0 + \sum \gamma_i \tau + \sum \delta_i \quad (3)$$

Consequently, PFE can be defined as:

$$PFE = 1 - S(t) \quad (4)$$

In this case, test interval (τ) refers to the time between training, or between assessment programs. The rate of the adjustment (γ) and training (δ) can be different from time to time and person to person.

Markov method for ship operations

Markov method is employed to model ship operations. Two conditions are recognized: normal condition and extreme condition. Extended from the model in Figure 1, the human performance is separated into three different functions: (1) monitoring the situation, (2) analyzing the situation and making the right decision, and (3) conducting the proper action. The complete model can be seen in Figure 6, and the descriptions in Table 1 and Table 2.

Notation N or n stands for normal condition and E or e for extreme condition. Transfer rate from normal to extreme is α_n and α_e is the reverse. The states numbering sequence is opposite to Dhillon (2003). Here, the lower the number showing the worse the condition.

A vessel is assumed to be safe (in state 4), when the crew perform all their tasks correctly: monitor the situation, make the right decision and conduct the proper action. Any crew can fail doing his or her task, and bring down the vessel into lower states (3, 2 or 1). The most likely path is that the crew fail to monitor the situation (a_{43}), which then leads to wrong decision (a_{32}), and obviously to improper action (a_{21}).

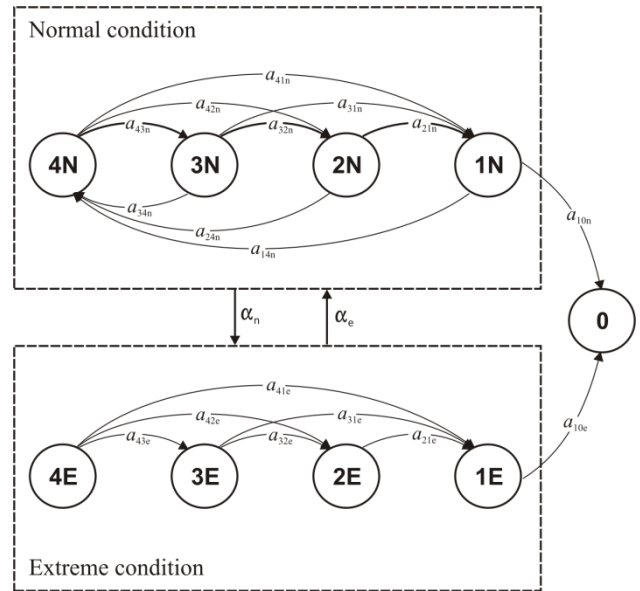


Figure 6. Markov model for ship operations

System State	Descriptions
4	The crew manage to perform tasks correctly
3	The crew fail to monitor the situation
2	The crew fail to make the correct decision
1	The crew fail to conduct the proper action
0	The vessel fails to maintain integrity

Table 1. System states for ship operations

Transfer rate	Descriptions
a_{43}	crew failure rate in monitoring the situation
a_{42}	probability of making wrong decision, given correct information
a_{41}	crew failure rate to conduct improper action, given correct information
a_{32}	probability of making wrong decision, given incorrect information
a_{31}	crew failure rate in conducting the proper action given incorrect information
a_{21}	probability of conducting improper action given incorrect decision
a_{10}	vessel's failure rate, given the crew fail to operate the vessel properly
a_{34}	monitoring restoring rate
a_{24}	decision making restoring rate
a_{14}	proper action restoring rate

Table 2. Markov transition rates for ship operations

In normal condition, the crew may realize their mistakes and restore the situation back to previous state. It is assumed that when the crew recognize their mistakes, they will put the situation back to the initial state. The likelihood to bring the back the situation to is called the restoring rate. In extreme condition, the chance to re-establish the situation is very low that no restoring rate is indicated.

It is important to identify what are the probabilities of each states to occur, especially states 1 and 0 ($P_1(t)$, $P_0(t)$). Those parameters represent the likelihood of fatal incidents to take place during a certain time. It is also essential to know the mean time to system failure (MTTF_S). Solutions for those parameters can be found in Rausand & Høyland (2004).

CASE STUDY: THE CAPSIZE OF HERALD OF FREE ENTERPRISE (HFE)

Brief summary of the accident

On March 1987 MV HFE left Zeebrugge for Dover. The weather was nice. The vessel was trimmed by bow and overloaded. The bow doors were still open (DOT, 1988, Kristiansen, 2005). The assistant bosun who was supposed to close the doors, left and went to bed. The bosun saw the situation, but did not do anything. The officers on the bridge were not aware of the situation. The vessel proceeded to sea. The master and the chief officer set the speed combinator to 4 and 6, expecting 10 to 12 knots and 15-16 knots respectively. On passing the Outer Mole, the master set all combinator to 6. Then, the accident took place: water flowing in, the bow freeboard decreased, the vessel dug deeper and finally capsized.

SIS Model on HFE case

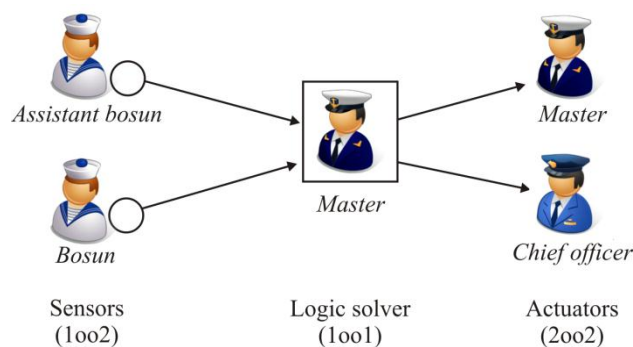


Figure 7. Crew modelled as SIS in HFE accident

The assistant bosun and the bosun are modelled as the sensors. The master serves as the logic server. At the same time, the master, together with the chief officer perform as the actuators.

The sensors fail to give the right information to the logic server. The master, assuming that all the procedures had been completed, then decided to proceed and perform the wrong action, i.e. went to sea with the bow doors open.

Markov model in Figure 8 is developed to describe the HFE accident. Some modifications are made from the generic model in Figure 6.

The states are defined and presented in Table 3.

Markov model on HFE case

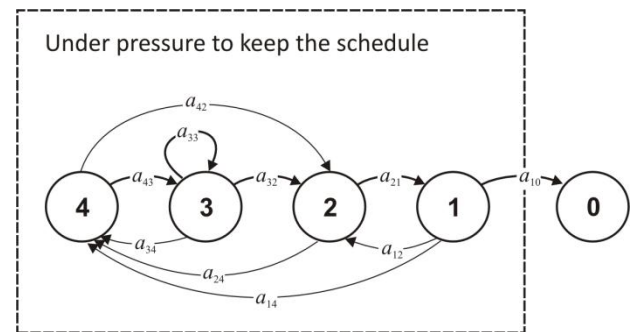


Figure 8. Markov model for HFE accident

System State	Descriptions
4	The crew manage to perform tasks correctly
3	The deck crew fail to monitor deviations on board
2	The master fail to make a proper decision
1	The bridge officers fail to operate the vessel properly
0	The vessel fail to maintain integrity

Table 3. System states in HFE accident

The transfer rates presented in Table 2 are also applicable for this case. A couple of transfer rates which do not apply in the case: a_{41} and a_{31} are omitted. Two transfer rates are added: a_{33} and a_{12} . The first one represents the crew failure rate loop rate, from wrong monitoring, back to the same state. In HFE case, there was a change of crew which gave them a chance to re-examine the situation and correct their performance. However, the bosun, like his assistant, did the same mistake and did not inform the bridge that the bow doors were still open. The latter represents similar loop in the actuators. The actuating state can be long and it can go back to same state. However, it is assumed that a transition rate to the state 1 itself (a_{11}) should be done through state 2. Therefore, a_{12} is defined. In the case of HFE, it was mentioned that the master decided to operate the vessel by regulating the combinator at 4 and 6. Subsequently, he changed them all to 6.

DISCUSSION AND CONCLUSION

Two models are adapted from the hardware reliability perspective to model survivability of ships. Markov model and SIS model are utilized to calculate human elements as the barrier systems on ship operations. Both models look potential to be used as retrospective as well as predictive tools. They provide holistic approach in analyzing the problems which can comprise of many scenarios. Yet, the methods are simple, practical and manageable to administer and to comprehend.

The Markov model offers the opportunity to accommodate the dynamic nature of most of the

problems faced at sea. Unlike existing publications (Redmill & Rajan, 1997, Carey, 2001, Cacciabue, 2004) which consider human factors as an influencing factors to SIS, this article treats human elements as the SIS.

Further validation for both models is required. At this stage, only qualitative models are presented. Further quantitative data and analyses are also required.

Combining both models with simulator-based methods will be an advantage.

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