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Abstract:

Several studies have shown that lifeboat was not as safe as it was supposed to be. Even though there is less number of lifeboat accidents that contribute to the total shipping accidents, lifeboat accidents caused a lot of fatalities and injuries to seafarers, most in maintenance, survey or drilling. Seafarers' confidence of lifeboats was seriously reduced.

In this report, a coding structure is proposed after analyzing several lifeboat accidents by using one primary method called Events and Causal Factor Charting (ECFC) and an assisting method called Influence Diagrams. Further, the probabilistic model is proposed by utilizing the Bayesian Belief Network (BBN) to help build a model for analyzing the relationship between different causal events (variables). A human and organizational factors analysis is carried out after the BBN approach. A Human Factors Analysis and Classification System (HFACS) is proposed in that chapter.

A specific coding structure for lifeboat accidents is addressed in the research. This could help collecting lifeboat accident data in a more professional way and provide the sounding data support for the future quantification work. The BBN and HFACS work was proved to be feasible and beneficial for the analysis of lifeboat accidents. Future technical analysis could be provided based on the research.

Keyword:

Lifeboat, Influence Diagram, Coding, BBN, HFACS

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Analysis and Coding of Lifeboat Accidents

A Thesis in the Field of Marine Technology for the Degree of Master of Science

Norwegian University of Science and Technology (NTNU)

2010/6/14

By：Jiawei Zou

ABSTRACT

Several studies have shown that lifeboat was not as safe as it was supposed to be. Even though there is less number of lifeboat accidents that contribute to the total shipping accidents, lifeboat accidents caused a lot of fatalities and injuries to seafarers, most in maintenance, survey or drilling. Seafarers' confidence of lifeboats was seriously reduced.

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Key Words: Lifeboat, Influence Diagram, Coding, BBN, HFACS

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I would also thank my classmate and friend Bin WANG studying Marine Structures who used to work with me day and night.

Jiawei Zou

June 14th, 2010

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CHAPTER1 INTRODUCTION

1.1 PROBLEM STATEMENT

It is common knowledge that humans are difficult to survive after an accident at sea. In order to reduce and control the risk of human losses under the acceptable criteria, measures and improvements have been taking all the time. Under the requirement that lifesaving appliances should be available for everyone on board a vessel, there are also improved design of lifeboats and their launching system. With the appliance of the lifesaving appliances, the risk of life loss should therefore be reduced.

The application of lifeboats and the corresponding regulations proposed by IMO or the local authorities mean that the lifeboats should be maintained under a high standard which needs skilled seafarers in practicing and real operation. Thereby, the risk of accident occurring during drilling or escaping increases. There are significantly a number of lifeboat accidents happened involving lifeboats, davits, winches, hooks and other apparatuses. Most of the accidents will result in injuries and some will cause loss of life. There have been lifeboat accident reports done by several marine safety branches in different countries. Because investigation reports vary from country to country, the difference of accident causes emerged. Some accidents were fully investigated due to the life loss and thus root causes were clear, while many others were less serious and they only identified the immediate causes.

1.2 SYSTEM DESCRIPTION AND LIMITATION

The lifeboat accidents here are regarded as lifesaving appliance accidents. In most conditions, it is the lifeboat system accidents including the lifeboat and the launching system of the lifeboat. Basically, the accidents mentioned in this thesis are lifeboat and its launching system accidents.

The main limitations of this thesis are constraints of accident data resources. Referring to a number of lifeboat accidents happened in different countries, it is impossible to find them all. Therefore, the analysis is only based on two or three marine accident databases. The regional limitation is yet unknown.

1.3 AIM AND SCOPE

1.3.1 AIM

This thesis aims at studying the lifeboat accidents and coding and evaluating risks of lifeboat accidents.

1.3.2 SCOPE

The objective of this thesis is to study the main causes of lifeboat accidents, to code the accidents from technical and operational aspects and then to apply Bayesian Network models in risk investigation of lifeboat accidents. The modeling approach is initiated from the study of several lifeboat accidents with the goal of identifying causal factors. The second step will be the construction of the Influence Diagrams indicating the interaction of different causal factors. Judging from the causal factors as well as accident types and miscellaneous aspects, build a coding structure for lifeboat accidents. The final step is to build BBN by using conditional probability tables which are based on the elicitation of influence diagrams.

The scope is explicitly divided into the following parts.

Case study of lifeboat accidents

Briefly describe the accidents needed to be analyzed. Lifeboat accident study should be started by categorizing work. Generalize the accident types as well as their causes.

Draw influence diagrams of each accident to establish a better insight and presentation into the accidents.

Based on the cases analyzed above, establish the influence diagrams of each case. Some basic scopes should be reached including the clear structure of influence diagrams, the root causes, external causes and the functions that link the cause and consequence. See if it is possible to establish a generalized influence diagram to be applied to the analysis of lifeboat accidents.

Study the effect of human factors on conditions of training and real situation.

Develop a proposal for the coding structure of lifeboat accidents both in technical and operational aspect.

It should be noticed that the importance of coding lifeboat accidents should be studied. Make comparisons between the coded accidents and free-text reported accidents.

Propose a coding structure for the accidents regarding to the technical and operational aspects.

Apply Bayesian Network approaches to support and evaluate the analysis.

Give a short description of Bayesian Network including its advantages by using BN to analyze data. See if there is any relationship between Bayesian Network and Influence Diagram in this study. Identify the variables of the accidents, structure BN, elicit numbers and calculate conditional probabilities if possible. Judge the possibility of finding the probability distribution.

1.4 ORGANIZATION OF THE THESIS

The thesis is organized as follows: Chapter 2 provides the literature study of previous studies had been done relating to the scopes mentioned above and the basic definitions of concepts and methods used in the thesis. Chapter 3 studies the lifeboat accidents. Chapter 4 describes the influence diagram applied to the accident analysis. Chapter 5 solves the coding scheme on the lifeboat accidents. Chapter 6 provides Bayesian Network analysis on the lifeboat accidents. Chapter 7 proposes an analysis and classification structure of human factors. Chapter 8 gives the discussion of the work done in previous chapters. All supporting details can be found in the appendix.

CHAPTER2 LITERATURE REVIEW

2.1 INTRODUCTION

In order to look for a salvation after the ship no longer to be able to secure the seafarers and/or passengers' lives, lifeboats or life rafts shall be considered as the first mean of escaping danger and be used under most circumstances. Compared to the application of lifeboats on larger ships, the scale limitation makes life rafts possible on smaller ships such as leisure boats. As one of the major ways to escape an accident, the safety of lifesaving appliances should be promised. However, as mentioned in the above chapter, there were unacceptable number of accidents reported involving lifeboat and its launching system accidents. Some of them even caused injuries and deaths to the seafarers. Accident investigations were carried out and some of the recommendations were submitted to International Maritime Organization (IMO) by different countries. In the report published by MAIB in 2001, evidence indicated that there were significantly number of accidents occurred under training and maintenance[1]. The IMO has indicated categories of accidents most likely to happen which are launching system failure and human errors[2]. From the technical part, newly designed launching systems were developed to make the launching and recovering work safer after the lessons of serious injuries and deaths[3]. Some investigations were made to examine the safe launching and recovering of lifeboats[4] and the application of new control systems in governing the descent speed of a seafaring vessel[5]. In order to reduce human losses, scale models and computer simulations were employed to reduce the costs and provide variable results. However, this raised another problem indicating human factors. Predicting the effects of human factors in the simulation still remains to be evaluated. Human errors are often cited as the major cause of accidents in a significant number of investigation reports.

Due to the unacceptable number of lifeboat accidents with crews' injury and sometimes fatality during drills and/or inspections, IMO proposed several regulations relating lifeboat accidents, lifeboat design, operation and maintenance to reduce the risk of lifeboat accidents. To evacuate passengers from large passenger vessels which are built for 5,000 or more people is considered time consuming and lack of deck space. Designing of state-of-art lifeboats and marine evacuation systems (MES) has never stopped. Norsafe has developed a new free fall principle lifeboat called Rescube which can make spontaneous evacuation from several decks possible and quick (See Figure1).

Figure 1 Rescube Lifeboat

Source: Norsafe AS

In the first section of the body structure, some definitions and working mechanism of lifeboat and its launching system are defined. The following sections will describe the researches previously done which relates the current research. The summary part summarizes the major projects described in the body structure. Analyses including the state-of-the-art, similarities/differences and strengths/weaknesses of literature are presented.

2.2 BODY STRUCTURE

2.2.1 BASIC KNOWLEDGE

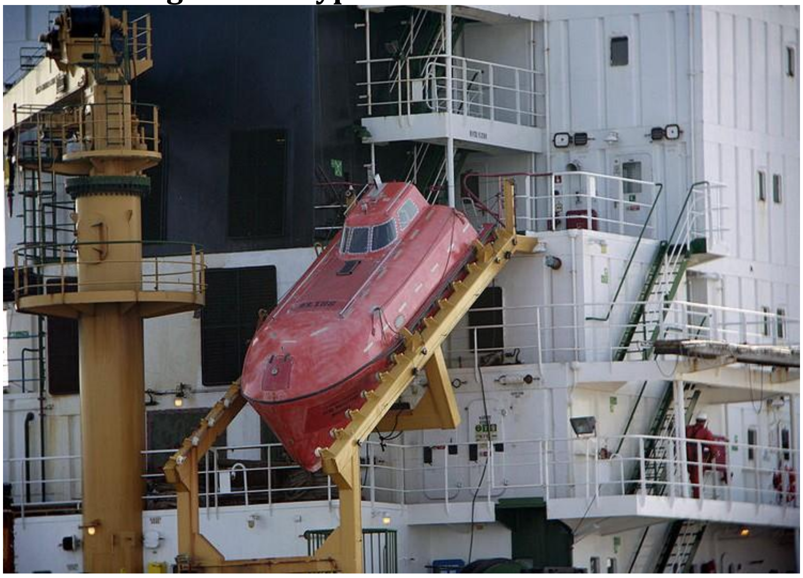
A lifeboat of which can be rigid or inflatable may be referred as a small watercraft carried on a ship to evacuation in the event of a disaster aboard the ship[6].

The inflatable lifeboat can also be treated as a life raft which is used on commercial vessels as the lifeboat does. The life rafts should allow automatic inflation by means of the stored high-pressure gas in a short time. SOLAS requires the life rafts to be sealed which means it should not be opened until there is an evacuation or inspection.

The main difference between lifeboats with life rafts is that the former is usually equipped propulsion system and can sail on its own power. A modern lifeboat is usually equipped an enclosed cover as protection of sun, rain, winds and waves.

Basically, there are two types of lifeboats categorized by its launching system. One is free-fall lifeboat and the other is normal lowering lifeboat. The free-fall lifeboat stored on a sloping slipway is able to be launched quickly by a quick release mechanism into water by free-fall gravity. It is designed to withstand the impact of water when entering the sea from a high place. The normal lowering lifeboat is lowered into water with the help of davits and winches. However, this requires more launching time than the free-fall lifeboats. Due to the specialty of the free-fall launching system, the lifeboat is only able to return with the help of the large crane. Figure2 shows a typical free-fall lifeboat installed on a ship.

Figure2. A Typical Free-fall Lifeboat



Source: http://en.wikipedia.org/wiki/File:CCNI_Magallanes_mg_5885.jpg

The other type can be lowered to water with release gears. There is regulation stating that lifeboat with full loads should be able to disengage from davit lines when it reaches or above the water. Some interlocking parts with hooks are attached to the lifeboat which allows the lifeboat to pivot and release under rotation[7]. The complicated design will consequently require an extensive training before seafarers can operate it. Since it is reversible, training, maintenance and repair are able to be carried out. Figure3 shows the picture of a normal lowering lifeboat.

Figure3. A Typical Normal Lowering Lifeboat

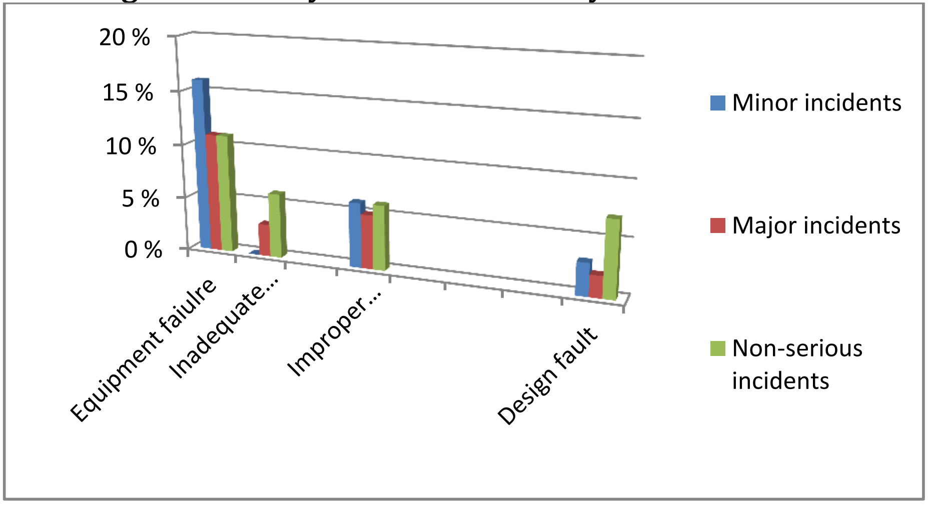
Source: http://www.offshore-technology.com/contractors/safety/norsafe/norsafe2.html

2.2.2 PREVIOUS RESEARCH

Joint Industry Survey: *Lifeboat Incident Survey-2000*

A joint industry survey was carried out by OCIME, INTERTANKO and SIGTTO in 2000[8]. There was a similar survey *Results of a Survey into Lifeboat Safety* done in 1994 by OCIMF and ICS highlighting equipment issues and availability on approximate technical information and documentation on board[9]. The subsequent survey was carried out under the continued lifeboat incidents. Several findings were listed after 89 returned completed questionnaires. Totally enclosed lifeboats with onboard release showed the majority 75% total incidents. The survey found that all incidents happened during maintenance (32%), emergency drill/exercise (35%) and survey (8%). It should be pointed that there were no lifeboat incidents or accidents happened under emergency situation. Primary causes of minor, serious and non-serious incidents are shown in Figure4.

Figure4: Survey Results of Primary Incident Causes



Injuries caused by equipment failure accounted for 50% while the other half human errors and design, operation inherent defect. In the report, surveys showed that there were little changes in incident types compared to the report of 1994. However, there were no fatalities reported in the report which was attributed to the awareness of the risks inherent with lifeboat operations by seafarers. The survey also showed the design and construction of lifeboats and their auxiliary equipment played significant roles in incidents of lifeboats.

MAIB: *Review of Lifeboat and Launching Systems' Accidents, 2001*

In 2001, Marine Accident Investigation Branch (MAIB) published a report regarding lifeboat and launching systems' accidents[10]. In the report, the general failures happened on lifeboat and launching system and the related causal factors were proposed. Some recommendations were made. Of 12 professional seafarers or 16% of the total lives lost on merchant ships and 87 people injured of a decade period were accounted by MAIB. All the accidents happened during training or testing with trained seafarers. The safety study also indicated that the lifeboat launching systems existed deficiencies causing injuries or deaths since significant accidents happened when embarking and recovering the lifeboat and subsequently lack of confidence of seafarers when doing operations. Except for redesigning lifeboat launching systems, maintenance of lifeboat systems, the training standards of seafarers are also proposed to reduce risks of lifeboat accidents. Since MAIB only accounted lifeboat accidents happened in UK territorial waters, the study cannot reflect the true scale of lifeboat accidents worldwide. Recommended studies of *value, need and desirability of lifeboats as well as the reported incidents and accidents worldwide with regard to the specification of lifeboat launching systems* to the IMO are therefore proposed by MAIB.

It should also be noticed that the Australian Maritime Services Board (MSB) also submitted a study of 9 lifeboat accidents involving lifeboats and design, maintenance and equipment deficiencies happened in 7 years to the IMO in 1999[11].

Trevor W Ross: *Ship's Lifeboats: Analysis of Accident Cause and Effect and its Relationship to Seafarer's Hazard Perception*

The project used questionnaires from seafarers as primary data and secondary data of lifeboat accidents from marine investigation departments to test 3 proposed hypotheses[12]. Hypothesis one supposed that *a correlation exists between lifeboat design as an established accident cause and the severity of injuries occurring.* To testify this hypothesis, the author combined cause with a severity analysis for the first time. Data collected showed that no confident conclusion can be drawn even if design was responsible for some incidents. Strategies *must address maintenance, training and design collectively, rather than treating them as individual issues.* Hypothesis two addressed *seafarers' perceptions of the hazards presented by lifeboats, and their associated systems, will be graded in the same order as those apparent from incident reports.* Results showed that this hypothesis was regarded as unproven because the hypothesis seemed true for operational hazards whereas untrue for component hazards. Besides, seafarers would sense more hazards even than they actually were. The third hypothesis showed *the perception of seafarers' will be that ship's lifeboats, and their associated systems, are fit for purpose.* In the report, the majority seafarers revealed positively to lifeboats and the author thereby considered hypothesis to be proven.

Miscellaneous IMO Reports

The IMO Maritime Safety Committee has approved MSC.1/Circ.1206[13] at its 81st session in 2006 to give recommendations on preventing lifeboat accidents suspending previous accepted reports MSC/Circ.1049[14], MSC/Circ.1093[15], MSC/Circ.1136[16] and MSC/Circ.1137[17].

2.3 CHAPTER SUMMARY

The majority of the above reports were done around 2000. Judging by the reports described above, evidence shows that they are basically focusing on the causal factors of lifeboat accidents and subsequently the improvement measures from lessons learned. These reports were strongly regional. Most of them as well as accident investigations were done by UK. Consequently the deviations with other countries are yet unknown. In the various reports, some basic accident classifications were done and causal factors were analyzed in details. Hence, some information in the previous studies is able to be applied to the thesis. The present lifeboat accident level is still unknown due to limited sources of marine casualties and incidents data. Although appeals of reducing lifeboat accidents stopped showing up after the MSC.1/Circ.1206 in 2006, it is still able to see lifeboat accidents involving casualties and injuries after that with initial causes of technical failure and human error from GISIS. There is a 3 years gap between the last investigations on lifeboat accidents and the current status with lifeboat accidents kept happening especially 3 GISIS reported accidents in 2007. Particularly, seeing through the report of Mr. T. W. Ross, a lot of uncertainties will be found which sourced from the questionnaire and hypotheses. In the risk assessment of an accident, data and information should be as complete as possible to perform an accurate analysis. As we know, owing to the inherent imperfect accident analysis, data and information will be uncertain more or less. Modeling assessments by applying probabilistic measures would be beneficial to get more reliable results. In the view of this, performing an intuitive visual format such as an intuitive visual format such as Influence Diagram and succeeding a Bayesian Network which is more and more popular in analyzing marine accidents could be significant and state-of-the-art.

CHAPTER3 ACCIDENT INVESTIGATION

3.1 SELECTION OF ACCIDENTS AND INVESTIGATION METHODS

The important role that accident investigation plays is to establish a better understanding of accident description, the root causes of accident and the risk reduction measures to prevent or reduce the similar accident from happening [18]. It can be seen that there are many different accident models and subsequently various accident investigation methods in application. Subsequently, the results will be different if different investigation methods are used.

There might be different sources to get the text description of lifeboat accidents. In order to subjectively study the causes of lifeboat accidents, the selection of accidents will be based on the investigation reports published by the local authorities. Due to the limitation of describing a significant number of accidents, there will be 3 accidents analyzed in this chapter and the next chapter which represent typical causes of accidents such as maintenance factor, human error, design defect, etc.

This chapter will focus on some lifeboat accidents and apply the primary accident investigation method Events and causal factors charting (ECFC) to the analysis of these accidents [19]. The secondary accident investigation method is addressed in the next chapter by using Influence Diagram as a complementary accident investigation method to show a better understanding of the accidents. The following table shows the two accident investigation methods are supplementary and subsequently can be used to give a better illustration of the accident analysis.

Table1 Characteristics of the Two Accident Investigation Methods

Method	Accident Sequence	Focus on Safety Barriers	Levels of Analysis	Accident Model	Primary/Secondary	Analytical Approach	Training Need
Events and causal factors charting	Yes	No	1-4	B	Primary	Non-system oriented	Novice
Influence diagram	No	Yes	1-6	B/E	Secondary	Non-system oriented	Specialist

Experience shows that there are minor accidents resulted from one cause. The majority accidents were caused by multiple factors that would interact. Events and causal factors charting graphically displays the accident in chronological sequences. It is primarily used for assembling the evidence to portray the accident sequence. The accident is depicted through the primary events sequence, the secondary events sequence and conditions influencing the events. The primary events sequence causing the accident is drawn horizontally and chronologically whereas the secondary events are added to the events and causal factors when appropriate. Conditions that will affect the events are placed above or below the events. The basic frame of the Events and Causal Factors Charting is illustrated in Figure 5.

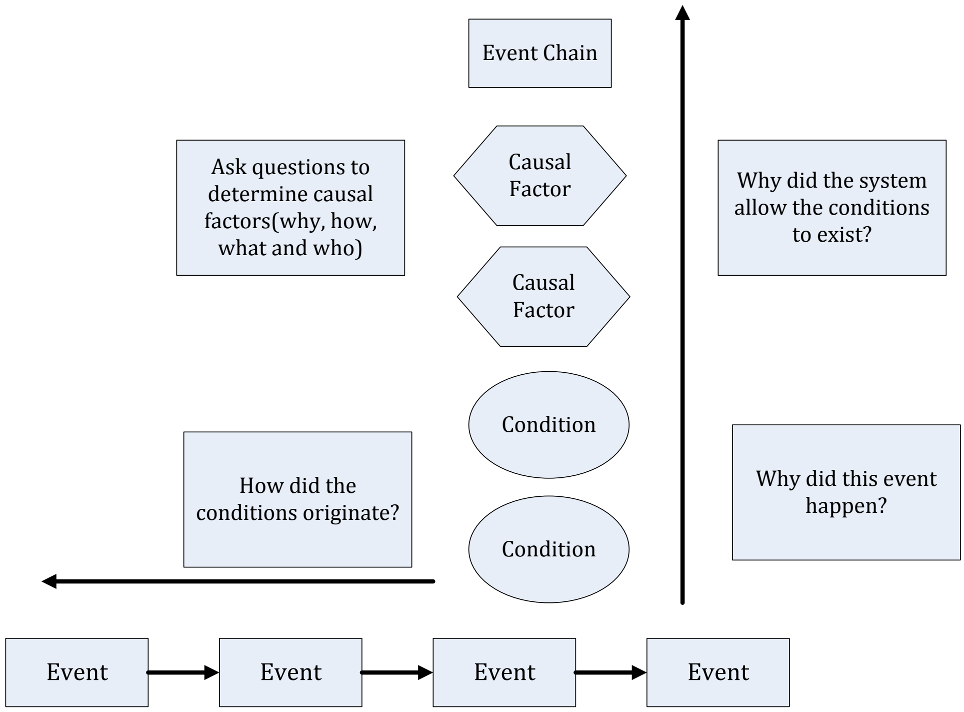
In this investigation method, the causal factor is also defined and subdivided into 3 categories which are separately direct cause, contributing cause and root cause.

Contributing Cause: An event or condition that collectively with other causes increases the likelihood of an accident but which individually did not cause the accident. (DOE, 1997)

Direct Cause: The immediate events or conditions that caused the accident. (DOE, 1997)

Root Cause: The causal factor(s) that, if corrected, would prevent recurrence of the accident. (DOE, 1997)

Figure 5: Events and Causal Factors Charting



3.2 ACCIDENT INVESTIGATIONS

There will be Events and Causal Factors Charting analysis of 3 typical lifeboat accidents in this section. The detailed text description of accidents is presented in the appendix 1.

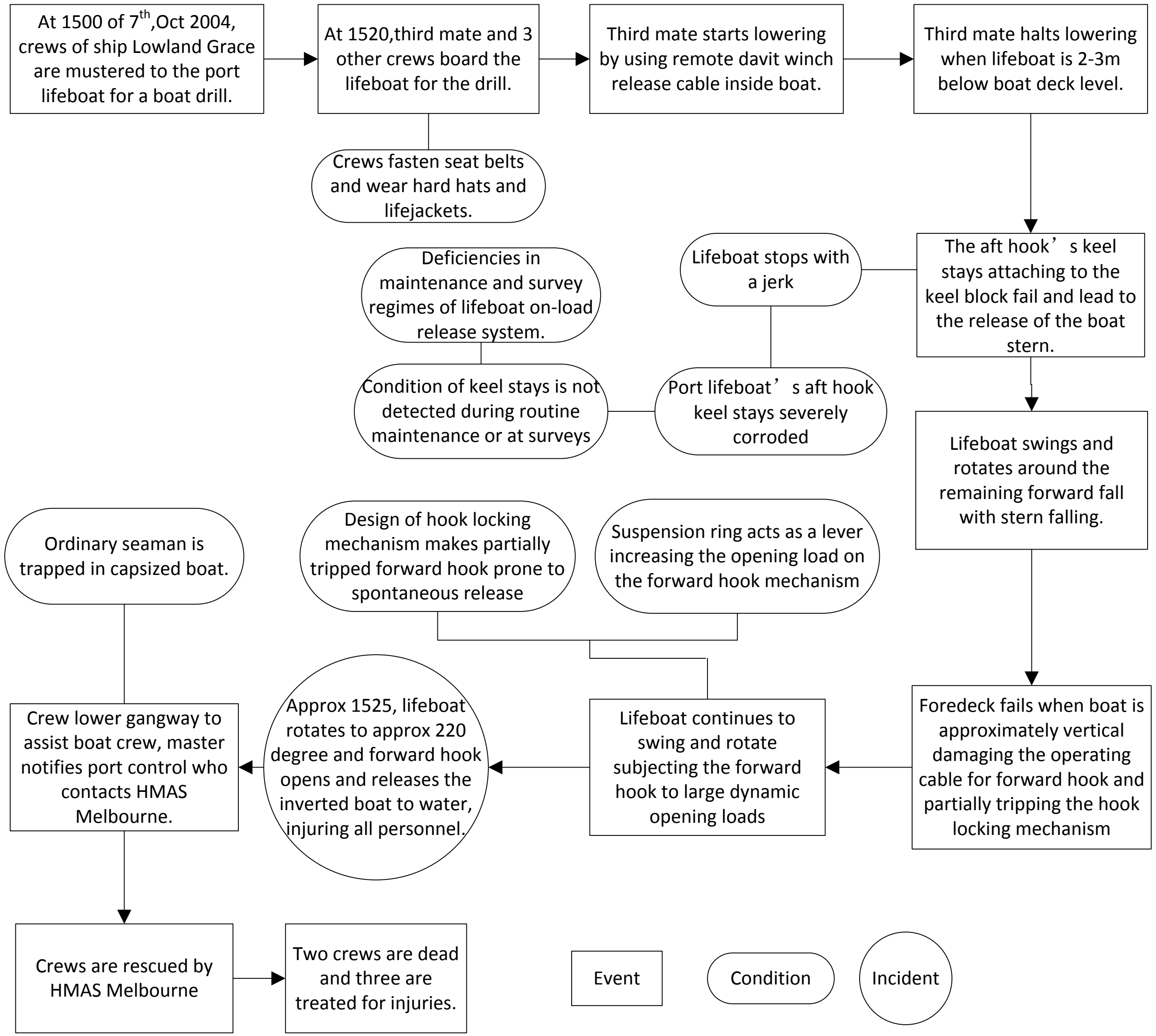
3.2.1 LIFEBOAT ACCIDENT AND FATALITIES OF HONG KONG REGISTERED BULK CARRIER LOWLANDS GRACE

For this accident, the Australian Transport Safety Bureau (ATSB) has already published an independent investigation into the accident with an ECFC. A modified one is shown in Figure 6.

As addressed in the chart, it is possible to find that the root cause is the maintenance and survey regimes deficiency which caused the ignorance of keel stay conditions and subsequently keel stays severely corroded. It is also mentioned in the Recommendation part of the investigation report that maintenance and survey regimes should thoroughly inspect and monitor the keel connection condition for lifeboat hooks.

Obviously, the failure of the aft hook keel stays due to severe corrosion directly caused the release of the lifeboat stern and the succeeding forward hook open which released the lifeboat thoroughly. This should be treated as the direct cause. After the aft hook keel stays failed, there are two contributing factors accelerated the release of the forward hook, the design of hook locking mechanism makes partially tripped toward hook prone to spontaneous release and the suspension ring acts as a lever increasing the opening load on the forward hook mechanism. It is also indicated in the Recommendation part that the design company should review the design of their on-load release system in light of the *Lowlands Grace accident*.

Figure 6 *Lowlands Grace*' s Events and Causal Factor Chart



3.2.2LIFEBOAT ACCIDENT AND INJURY TO CREW ABOARD THE PANAMA FLAG BULK CARRIER CAPE KESTREL

Regarding this incident, the Australian Transport Safety Bureau published the investigation report including the ECFC analysis. A modified ECFC is presented in Figure 7 in the following.

Judging from the investigation report, there are several factors contributing to the incident. It can be regarded as human errors which result in the incident. Because of the partition of the forward falls and following the aft falls, the lifeboat fell into the sea with bow first. That could be regarded as the direct cause.

The following described can be addressed as the contributing factors:

With the hoist button on the winch remote control unit not operating and the fault that resulted in this not identified and rectified, the boat was hoisted manually by pushing in the winch motor contactor in the starter panel which located in the air conditioning room.

For the first engineer in the air conditioning room, the noise hampered him from communicating with the mate. He was also unable to see the boat station from that position.

For the mate who ignored the instructions of the master that crews should disembark at the main deck, he also was not aware of how the boat was being hoisted and the consequence of manually using the contactor to hoist the boat. The consequence turned out to bypass safety systems.

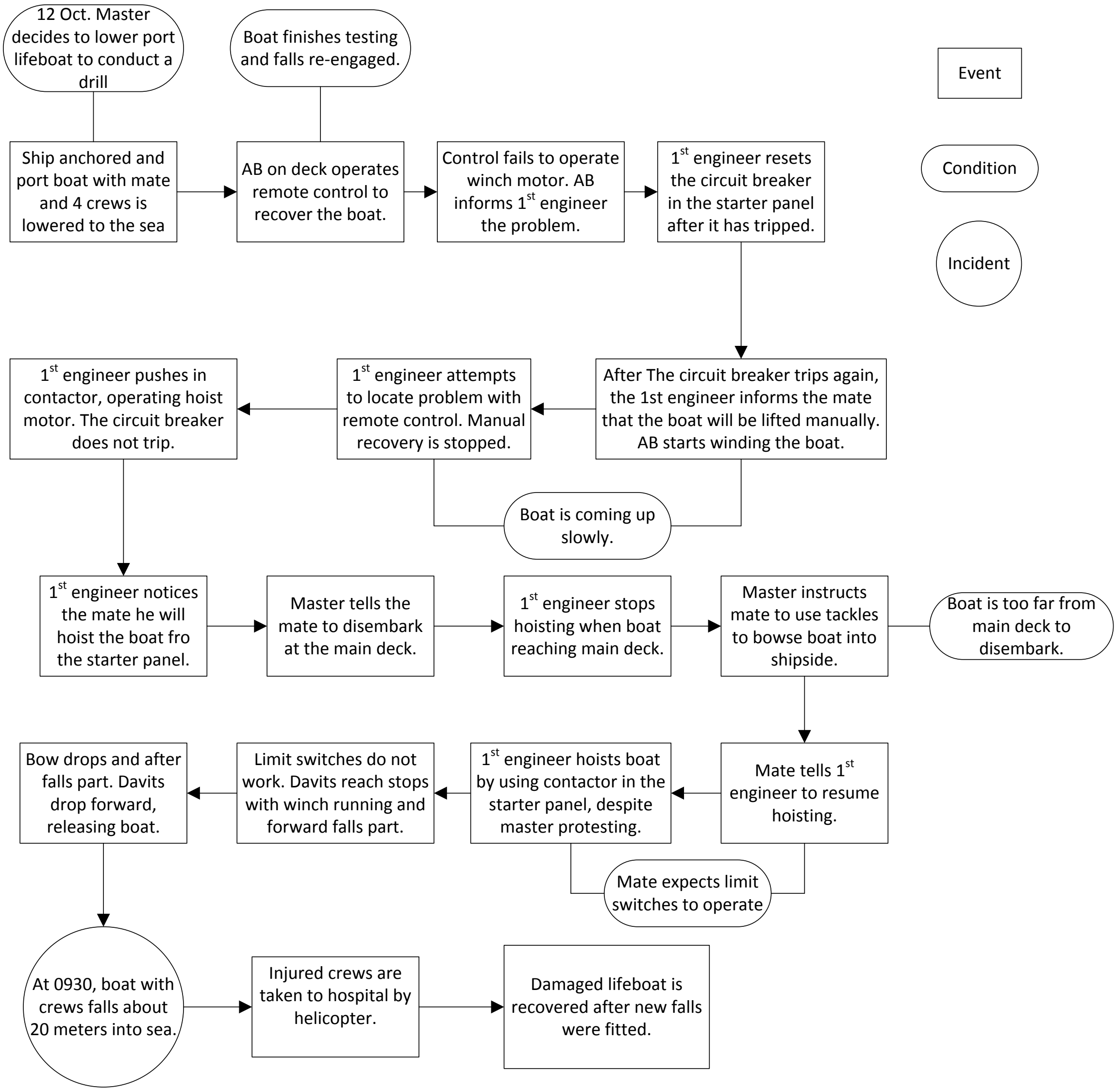
Probably, the clutch lever was not in the correct position for turning the boat in and as a result, the boat came in too fast.

For the 1st engineer and the chief engineer, both of them should have known that it was obligatory that hoisting of the boat should cease before contact was made with the limit switches on the frame of the davits. The boat should have been turned in manually after exceeding the threshold. The first engineer seemed not aware of the fact that the limit switches had been bypassed. The chief engineer did not notice him as well.

The above can be treated as the root causes of the accident. If the engineers were aware of the operation regulations, the accident would have been prevented.

Attentions to the operation hazard while operating the winch with the contactor should be drawn and warning notices should be posted. All the documentations and all personnel training for maintenance, inspection and adjustment of lifeboats, launching appliances and associated equipment should be in accordance with relevant ISM codes. Self-launching cradle stoppers are recommended for manufacturers for the purpose of preventing the davits dropping under the circumstance of broken fall wires.

Figure7 *Cape Kestrel* Events and Causal factor Chart



3.2.3LIFEBOAT ACCIDENT AND INJURY TO CREW ABOARD THE FRENCH REGISTERED ANTARCTIC SUPPORT VESSEL L'ASTROLABE

Based on the investigation report published by ATSB, a modified ECFC is presented in Figure 8.

It is pointed out in the report that there is no hand holds attached to either in the fall block or the suspension ring which means that the crew in the lifeboat had to handle the blocks and rings directly by manhandle. It also indicated that the lifeboats on the ship were not required to equip foul weather recovery strops which, with the presence, could have prevented the danger of swinging fall blocks to the lifeboat crew. The above, on the other hand, can be treated as the root causes. If either above described was fitted, it could have prevented or at least reduced the risk of the accident. The direct cause of the accident can therefore be considered as the second engineer caught his thumb while attempting to secure the aft fall. The contributing causes are listed below:

There was no painter left to be attached to the forward fall block after the boat departed to rescue the 4-8 crew member.

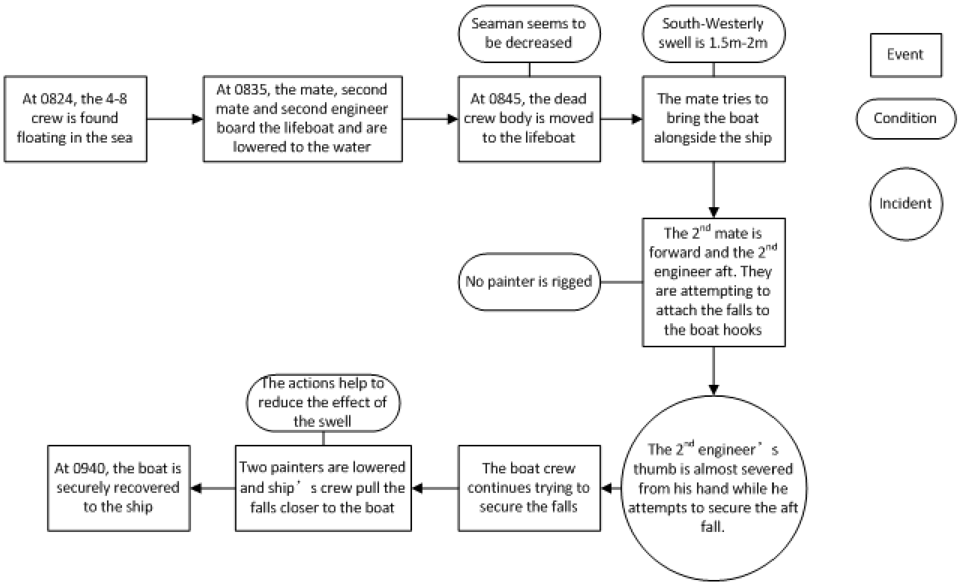
The vessel motion in the seaway made it difficult to recover the lifeboat and caused damage to the lifeboat and its fittings.

Some recommendations were made to reduce the risk of this kind of accident. It includes the follows:

For totally enclosed lifeboats, it should be considered to replace suspension rings attached to the lifeboat's fall blocks with preferably designed rings attached with 'hand holds'

The foul weather recovery strops should be considered to be provided. It also suggested the Flag State should refer it to the International Maritime Organization for consideration.

Figure 8 L'Astrolabe Lifeboat Events and Causal Factor Chart



CHAPTER 4 INFLUENCE DIAGRAMS ON LIFEBOAT ACCIDENTS

In this chapter, the influence diagrams will be applied to the accidents analyzed in last chapter. The purpose is to find out the how the causal factors interact with each other. Based on the influence diagrams, judge the influence of human factors contributing to the accident causal factors.

4.1 DEFINITION OF INFLUENCE DIAGRAMS

An influence diagram is a simple graphical and mathematical representation of a decision problem. It is considered as a model which combines Bayesian networks and decision making problems in fixed orders.

An ID is a directed acyclic graph consisting of nodes and arcs. In order to simplify the drawing workload, the software ***Microsoft VISIO*** is used to construct the IDs. The following illustrates the definitions and sketches of the basic components.

Nodes:

Decision: A decision is a variable drawn as a rectangle that is able to be controlled by a decision maker.

Chance: A chance variable is drawn as an oval which means uncertainty and unable to be controlled manually.

Objective: An objective variable is represented by a hexagon indicating the criterion that a decision maker is trying to maximize or minimize.

General: A general variable is a deterministic function of quantities it depends on. It is drawn as a rounded rectangle. Typically, it is usually used to represent a deterministic quality or functional relationship.

Arcs: An arrow or arc denotes the influence which expresses knowledge about relevance. It does not necessarily represent a causal relation or a flow of material, data or money.

4.2 CONSTRUCTION OF THE INFLUENCE DIAGRAMS

In order to build the specific ID for each accident, a basic understanding of how the accidents are categorized is essential. This section aims at the construction of the generalized influence diagram and the provision of evidence for the building of Bayesian Belief Network (BBN) in the final chapter.

Before starting, there are a few considerations needing to be noticed:

There is no such model that was built before. The causal factors for the lifeboat accidents are miscellaneous and therefore difficult to be modeled totally. Based on the risk influence model developed by SINTEF Industrial Management for North-sea helicopter transport [20], a modified model is developed in the following.

There will be two IDs which are consisted of frequency of incidents/accidents (I/A) and consequence of I/A.

There are three levels of risk influencing factors (RIFs) in the frequency influencing diagram described in the report mentioned above: operational, organizational and regulatory & customer related. It is considered the same case as in the marine industry and thus can be applied to the modeling of the generalized ID of frequency. They are also applicable for the structure of the consequence ID.

Generalized influence diagrams are built as shown in Figure 9 and Figure 10. For the frequency ID, as can be judged from the above, the objective variable is lifeboat accident frequency. The decision variables are represented by the technical dependability, the operational dependability and the external environment which are augmented with the chance variables such as design, operation procedure, sea, etc.

Accordingly, the accidents investigated in the former chapter will be developed based on the generalized ID.

Figure9. Generalized Influence Diagram in Frequency of Lifeboat Accidents

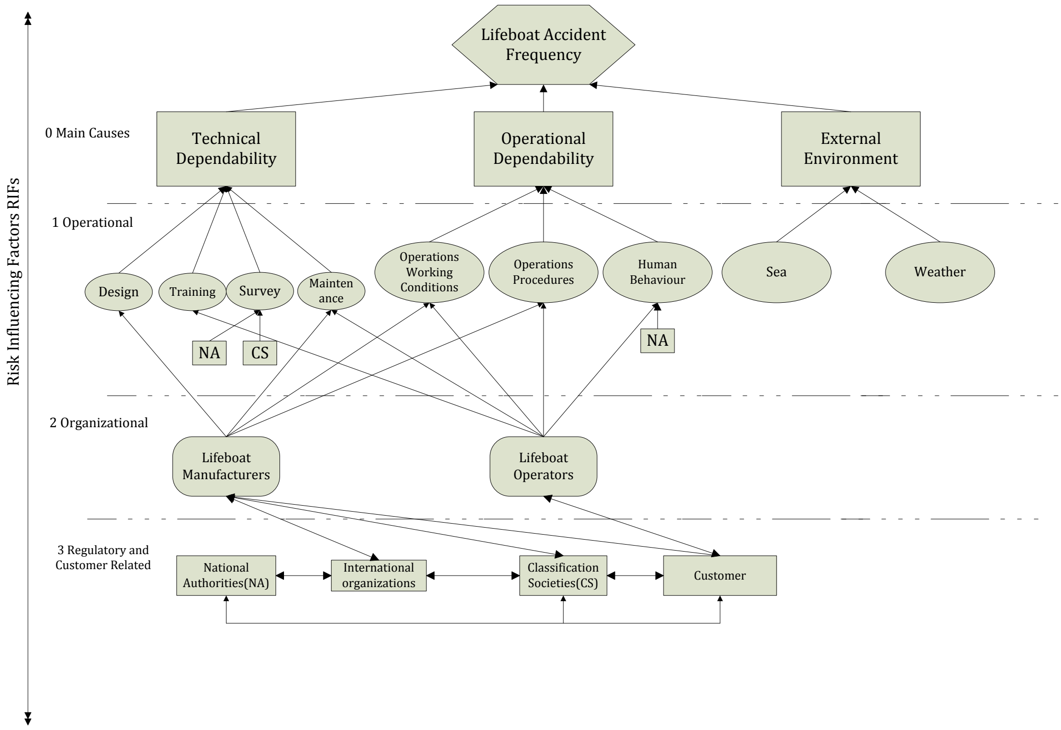
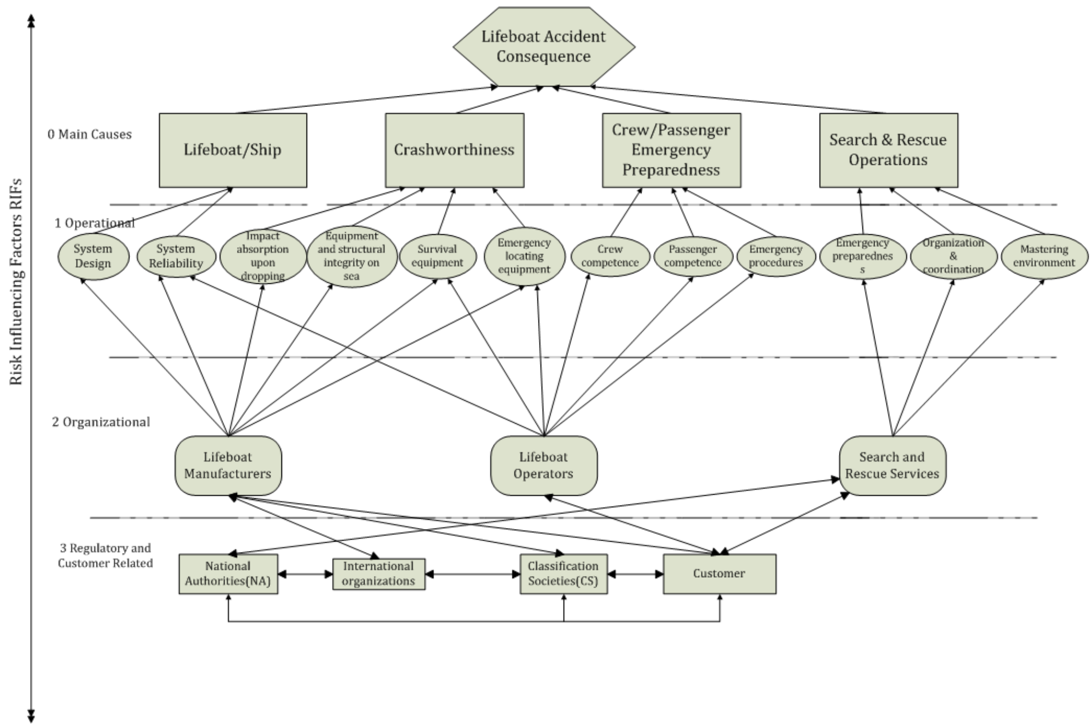


Figure10. Generalized Influence Diagram in Consequence of Lifeboat Accidents



4.3 SPECIFIC DEFINITIONS OF VARIABLES

There are some definitions that have appeared several times in various reports or regulations. Due to the above reason, the following only lists the definitions needing explanation.

4.3.1 VARIABLES IN FREQUENCY ID

Decision Variables:

Operations Working Conditions: Factors consisting of physical working conditions and organizational working conditions that influence the crew's ability to perform the required tasks.

Operations Procedures: Procedures covering all aspects with releasing and recovering of a lifeboat required by SOLAS and LSA, including the operation manuals of lifeboat and its launching system, the checklists, etc.

4.3.2 VARIABLES IN CONSEQUENCE ID

Equipment and Structural Integrity at Sea: No significant damage to hull and equipment and being able to perform the function of life-saving appliance after contacting with sea and/or subsequent operations at sea.

4.4 INFLUENCE DIAGRAM FOR EACH ACCIDENT

Based on the above frequency and consequence IDs generalized for the lifeboat accidents, specific analysis for each accident in last chapter is presented in the following figures (Figure11-Figure16).

4.4.1 FREQUENCY AND CONSEQUENCE IDS FOR LOWLANDS GRACE ACCIDENT

As indicated in the official investigation report, there is recommendation to the manufacturer suggesting the redesign of the on-load release system in view of the *Lowlands Grace* accident and other incidents involving on-load release systems of similar design. Here, it is treated as existence of design failure. For consideration in accordance with the definition of Customer in the ID, ship owners, managers are treated as the customer. Recommendations to the statutory authorities, classification societies, customer and international organizations are thus treated as the existence of survey and maintenance regime deficiencies including the operations procedures. The frequency ID is therefore presented in Figure 11.

As mentioned above, there exist design deficiencies which will result in the reduced reliability of on-load release systems of the lifeboat. The lifeboat accident consequence mitigation is able to be realized if there are improved design and systems reliability. Referring to the crashworthiness, the absorption of impact energy by lifeboat will eliminate the energy absorbed by human body and thus provide the first protection layer. The survival equipment enables the further protection of the human body. Here it is regarded as the helmet, the lifejackets, etc. When contacting with water by accidental release, the ability to maintain structural integrity and normal floating conditions provides the seafarers inside the lifeboat probabilities to escape the hazard. The fast reactions of the rescue team as well as the first aid provided by the seafarers on board are able to reduce the liability of seafarers in the lifeboat from suffering further harms. Obviously, in this accident, the lifeboat capsized accompanied with structural failure and thus caused the deaths and injuries to the seafarers inside the boat. Figure 12 represented the consequence ID for this accident.

Figure11. The Frequency ID for *Lowlands Grace* Accident

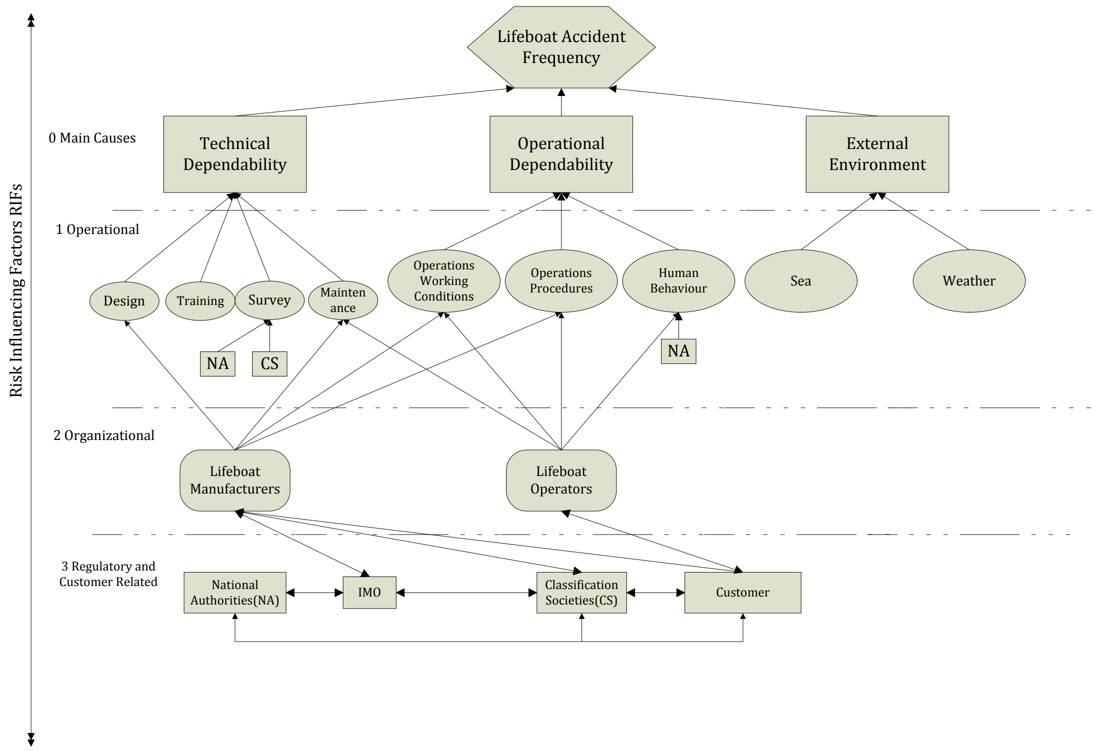
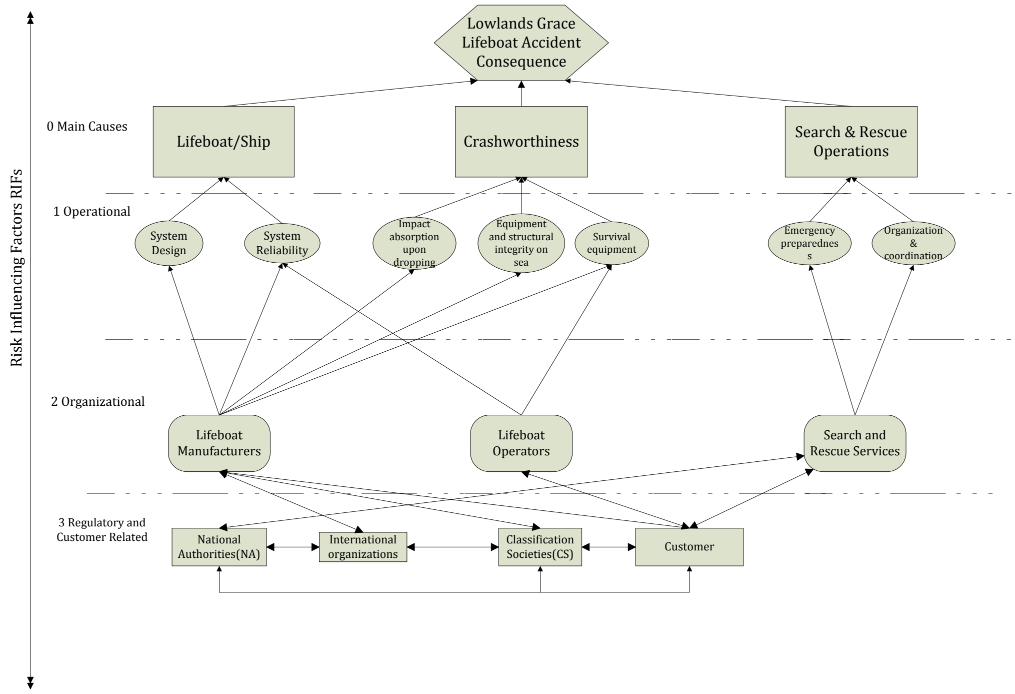


Figure12. The Consequence ID for *Lowlands Grace* Accident



4.4.2 FREQUENCY AND CONSEQUENCE IDS FOR CAPE KESTREL

Accident recommendations indicated several aspects with respect to the technical and operational aspects. From the technical review, the training and the maintenance and survey are requested to be executed strictly under several regulations. It can be interpreted as the technical deficiencies in ship owners and operators from one hand. From the other, it also indicates that the operations working conditions, the operations procedures and the human behavior are not satisfactory under the very scenario. It is able to be improved by following the regulations/rules strictly and thus reduce the risk of operational factors.

For the lifeboat manufacturers, there is maintenance recommendation by fitting another equipment to prevent the same accident. See Figure 13 for the frequency ID.

In this accident, the improved system design, referred as the fitting of self-launching cradle stoppers, could improve the system reliability and prevent the davits from dropping and subsequently prevent the lifeboat accident. There are reports of glass broken at the front hatch and causing water inlet. The water inlet stopped when the bow rose. Personnel wearing protecting equipment suffered injuries only. It can be comprehended that the energy were absorbed by lifeboat and the protecting equipment which substantially reduced the amount of energy absorption for humans. However, if we review the accident, the crew competence such as the communication, the training…is insufficient. This could possibly cause a more severe accident if the lifeboat hardware system was relatively weak. The immediate response of ship crews as well as local rescue services reduced the subsequent risks when boat crews suffering injuries at sea. See Figure 14 for the consequence ID.

Figure13. Frequency ID for *Cape Kestrel* Accident

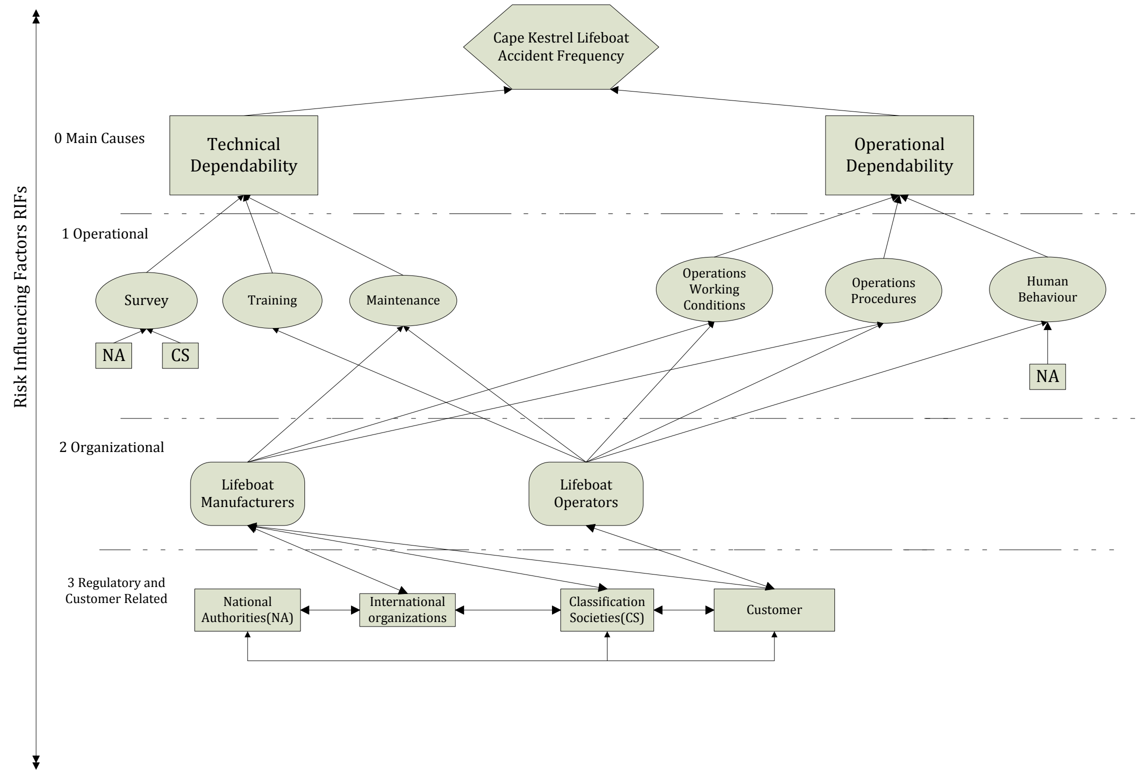
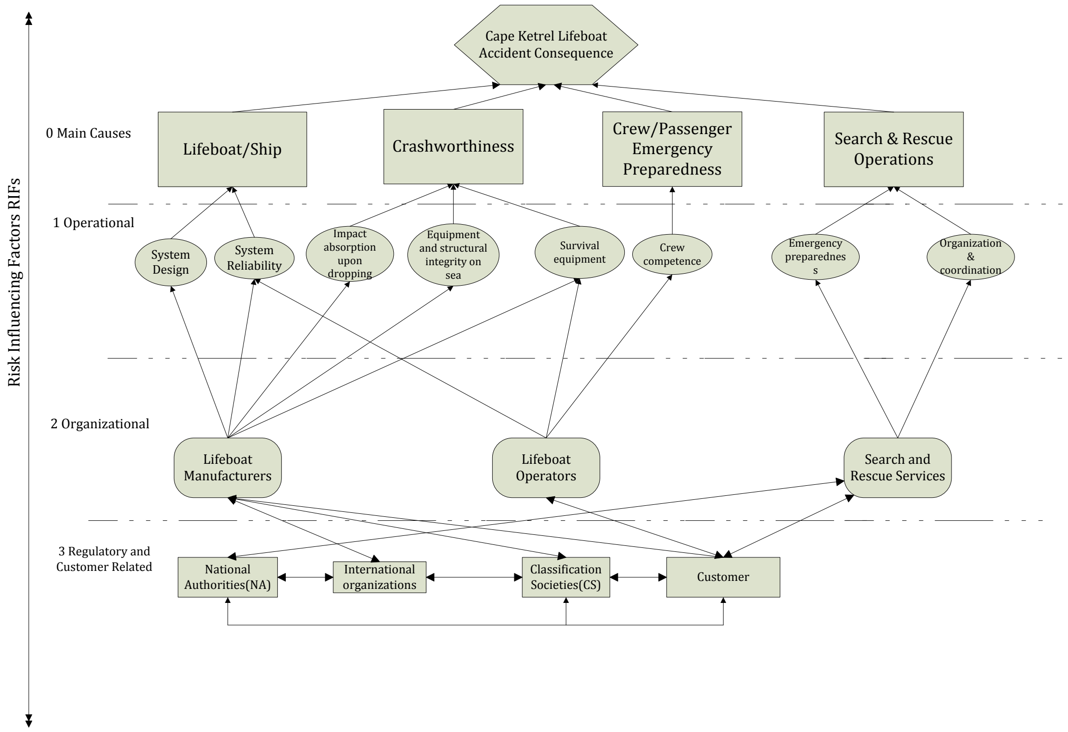


Figure14. Consequence ID for *Cape Kestrel* Accident



4.4.3 FREQUENCY AND CONSEQUENCE IDS FOR *L'ASTROLABE*

As can be seen from the analysis of last chapter, the inadequate design of suspension rings attached to the lifeboats' fall blocks caused the injury to the second engineer's right hand. In the recommendations due to this accident, a suitable design of suspension rings with 'hand holds' attached was proposed.

This could be attributed to the chance variable *Design* for manufacturers. The replacement of newly designed rings as well as another suggestion of providing foul weather recovery strops could be treated as *Maintenance*. It should be pointed out that the injury to the second engineer and his subsequent actions could possibly cause fear or psychological unstable to the remaining seafarers on board and thus elongate the recovery operation or cause further incidents. Thus, this is regarded as *Human factors* variable. In this accident, the swell introduced the difficulty in recovery operation. If the sea state is good enough, the risk of accident could be eliminated. The frequency ID is shown in Figure 15.

From the view of mitigating consequences, the proper design could significantly eliminate the consequence of injury. In case of the crews knowing the hazard when operating and the emergency procedures including the instruction of operation and rescue under hostile environment, the second engineer could have been able to avoid the injury. It is therefore added here. The report pointed out the recovery of lifeboat took about 70 minutes. This could possibly cause the added insult to injury. Therefore, it could be significant if the recovery is faster. Accordingly, the *mastering environment* variable is added here. See Figure 16.

Figure15. Frequency ID for *L'Astrolabe* Accident

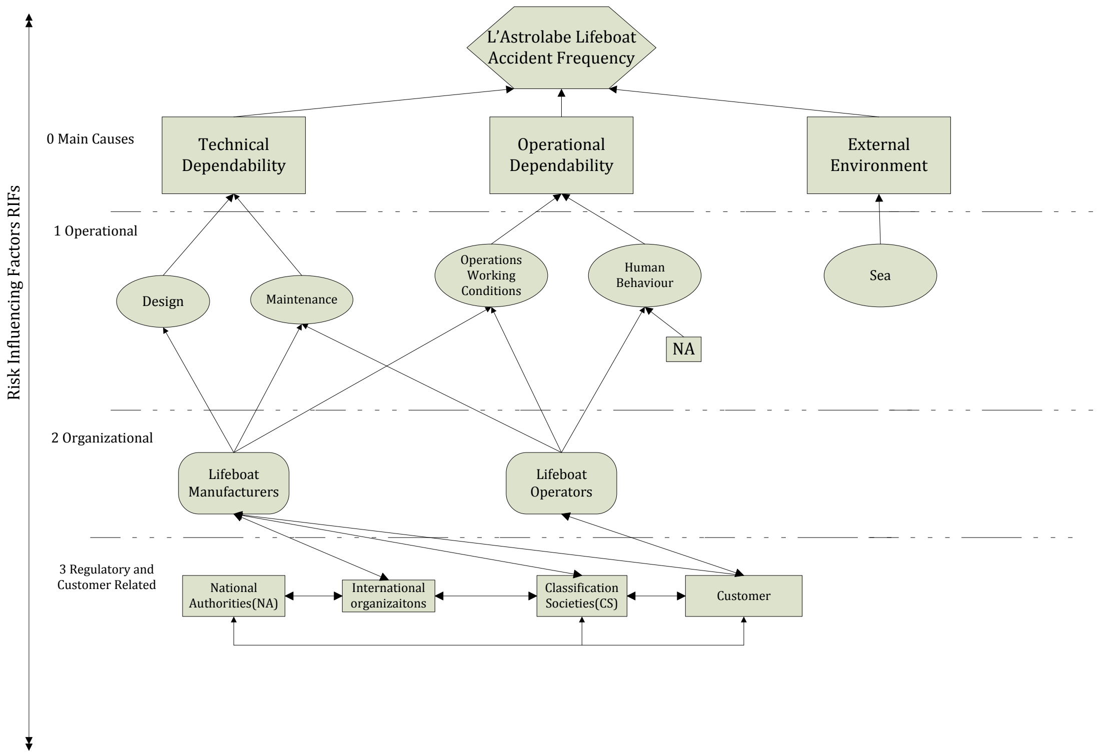
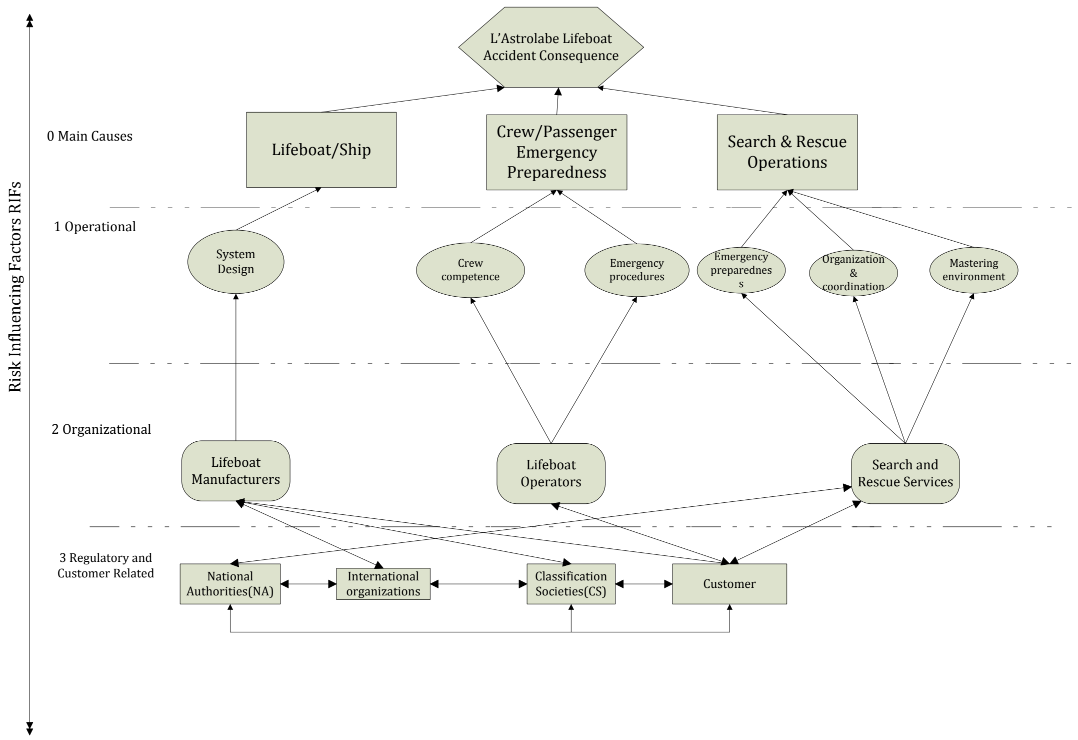


Figure16. Consequence ID for *L'Astrolabe* Accident



CHAPTER5 CODING STRUCTURE OF LIFEBOAT ACCIDENTS

This chapter will develop a coding structure for lifeboat accidents relating technical and operational aspects. Section 1 will introduce the basic procedures of building an accident database. Section 2 and 3 will develop a coding structure for lifeboat accidents.

5.1 INTRODUCTION TO ACCIDENT DATA CODING

Kjellén mentioned in his book '*Prevention of Accidents through Experience Feedback*'[21] that two important aspects separately *Data Type* and *Data Elements* must be specified in defining an accident database. For data elements, it can be regarded as types of facts included in each accident including date, place, etc. Data type can be treated as the way data is coded, for instance, nominal, ordinal, interval, ratio scale or free text. Following the decision of accident model selection based on the information quality and quantity as well as the efforts on investigation and result quality assurance, an accident database could be established.

Data with nominal, ordinal, interval or ratio scale here could be treated as the coded data. By searching for events meeting the criteria in ordinal, interval or ratio scale, it basically means to search accidents during a time scale or period. For example, to find lifeboat accidents happened in 2009 or injured person absent for more than 30 days. The nominal measurement means accidents under a specific condition such as accidents during maintenance. The coded data will enable the analysis of data in a structured and statistical way such as tables and diagrams, etc.

Free text descriptions will be used when matching certain words. For instance, match causal factors with design deficiency. The free text descriptions are unstructured and unsuitable for quantitative analysis. However, it promises the richness of data.

5.2 LIFEBOAT ACCIDENT CODING

In MAIB's investigation report on the lifeboat accidents, lifeboat accidents were blamed to be the major causes of deaths. Although several countries have realized this problem and several rules and regulations were also made to improve the lifeboat safety, there is still no systematic and generalized coding structure to record lifeboat accidents. A lifeboat accident coding structure is therefore needed to be proposed to show what happened and why it happened and furthermore, to provide the sound proof of improving the lifeboat safety.

Of different accident investigation reports published by different countries, there are some common parts which could be used to build the coding structure.

The introduction to basic ship characteristics and narrative of the accident

This will make up the basic information part of the coding structure. By entering the details to the accident database, search results such as time, place, weather, lifeboat details and accident summary can be reached. Especially, the summary part should at least contain key aspects such as time, location, task, main failure sequence and the subsequent rescue procedure to help the reader get a rough understanding of the accident.

The accident analysis

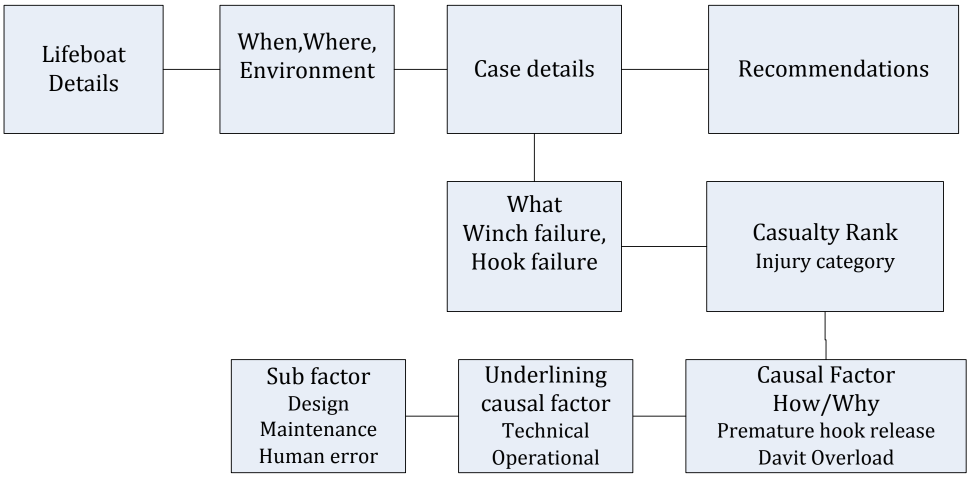
This part constitutes the main body of the coding structure. The causal factors should be therefore listed and classified according by the technical and operational aspect. The consequence of the accident is required to be addressed as well.

The concluding of causal factors and the recommendations to prevent further similar accidents

This part should be regarded as the supplement part of the coding structure to provide the recommendations to roles involved in the lifeboat accident.

Based on the aspects described above and combing the technical and operational consideration, a general proposal for lifeboat accidents is shown in Figure 17 to help to code the lifeboat accidents in a quantitative and qualitative way.

Figure17. General Coding Proposal for Lifeboat Accidents



Based on the coding proposal, a coding structure for lifeboat accidents is provided in the following section.

5.3 LIFEBOAT ACCIDENT CODING STRUCTURE

Table 2: Coding Structure: Basic Information of Accident

Basic Information of Accident			
1	Time of Incident	Date:	DD/MM/YYYY
		Time:	GMT& Local
2	Location	Place Name:	Name of port or other geographical reference
		Longitude:	
		Latitude:	
3	Environment	Wind:	Force (Beaufort Scale)
		Wave/Swell:	Height
		Ice Conditions:	Y/N
4	Lifeboat Particulars	Type:	Boat Code
		Length Overall:	m
		Draught:	m
		Propulsion:	Engine Type, Manufacturer
		Built:	Yard, Year
		Crew:	Capacity and Personnel Involved
		Launch Type:	Davit Launch/Free-fall
		Enclosed Type:	Y/N
		Classification Society:	
		National Authority :	
5	Summary	Free-text description. Should at least contain time, location, task, main failure mode and the subsequent rescue procedure.	

Table 3: Coding Structure: Casualty Data

Casualty Data			
6	Personnel Involved		
		Result of Incident:	Minor, Death, etc.
		Number:	
		Position:	Rank/ Passenger
		Gender:	M/ F
		Age:	
		Injury/ Missing/ Fatality Nature:	Cut, Drown, etc.
		Part of Body:	Leg, Arm, etc.
		Activities:	Survey, Emergency, etc.
		Incident Place:	Detailed Place of Ship/Lifeboat
7	Failure Mode:	Hook Failure, Bowsing failure, etc.	
8	Subsequent events if any:	Hull damage due to impact with water, etc.	
9	Lifeboat Condition:	Capsized, listing, etc. + Free-text Description	

Table 4: Coding Structure: Technical Contributions to Incidents/Accidents

Technical Contributions to Incidents/Accidents					
		Characters Involved	Severity	Cause Description	Others
10	Design	Operator, Manufacturer, etc.	Minor, Major, etc.	Free-text description	Recommendations, Notifications, etc. Free-text description
11	Survey	Operator, Manufacturer, etc.	Minor, Major, etc.	Free-text description	
12	Maintenance	Operator, Manufacturer, etc.	Minor, Major, etc.	Free-text description	
13	Training	Operator, Manufacturer, etc.	Minor, Major, etc.	Free-text description	

Table 5: Coding Structure: Operational Contributions to Incidents/Accidents

Operational Contributions to Accidents/Incidents							
		Personnel Involved	Type		Severity	Cause Description	Others
14	Human Violations/Errors	Crew, Passenger, etc.	Slip, Lapse, etc.		Minor, Major, etc.	Free-text description	Recommendations, Notifications, etc. Free-text description
		Physical	Psychological	Organizational			
15	Operations Working Conditions	Illness, etc.	Fear, etc.	Emergency, etc.	Minor, Major, etc.	Free-text description	
16	Operations Procedures	Manual, checklist, etc.			Minor, Major, etc.	Free-text description	

Table 6: Coding Structure: Additional Information

Additional Information	
Sequence of Events leading to Accident	Free-text Description
Actions be taken to Prevent Similar Accidents	Free-text Description

CHAPTER 6 APPLICATION OF BBN ON LIFEBOAT SAFETY STUDY

In this chapter, the feasibility of utilizing the Bayesian Belief Network on lifeboat safety study will be discussed. The steps are as follows:

Definition and example of BBN

Application of BBN on lifeboat accident analysis

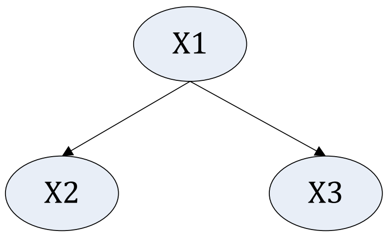
How to assign conditional probability tables

Modeling of BBN based on a specific case

6.1 DEFINITION AND EXAMPLE OF BBN

A Bayesian Belief Network which is also called directed acyclic graphical (DAG) model is consisted of a set of nodes and directed edges between nodes. The nodes here represent the probability distribution which might be continuous or discrete and the edges here mean the conditional probabilistic dependencies. A simple BBN is shown below.

Figure18. A sample of Bayesian Belief Network (BBN)



The node which arcs are directed into is often referred to as '*Child Node*'. Likewise, the node with arcs depart from is called '*Parent Node*'. In the above figure, the X_1 is called parent to X_2 and X_3, and X_2, X_3 is therefore regarded as the child of X_1. Nodes without parents are called *Root Nodes* and nodes without children are called *Leaf Nodes*. Nodes such as X_1, X_2, and X3 may have more values than true and false and not all relations have to be deterministic.

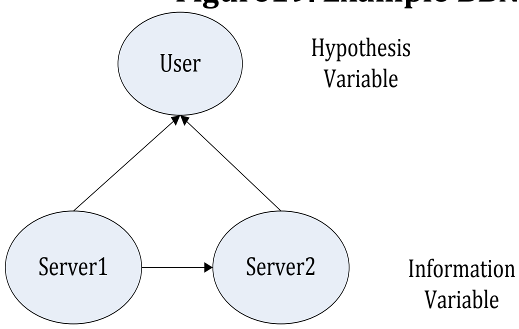
Bayesian Belief Network simply represents the qualitative and quantitative information. The qualitative part is treated as the whole structure which graphically shows the causal relationships of the variables. The quantitative part is treated as various conditioned probability distributions of variables.

To build a BBN, the following steps can be used:

First, to identify the problem or in other words what I would like to know. For example, estimate the probability of user receives the data packets through server 1. Assume the data packets can be accepted through server 1 and server 2. Also, suppose server 1 has a direct effect on server 2 which can be understood as server 2 will usually not transmit data packets when server 1 succeed in transmitting data packets to user.

A simple framework can be built with the information hypothesized above. In figure 19, 'User' is the hypothesis variable (Child). 'Server 1' and 'Server 2' are the information variables (Parents). The hypothesis variable is influencing the information variables. On the other hand, the information variables are indicating the hypothesis variable.

Figure19. Example BBN



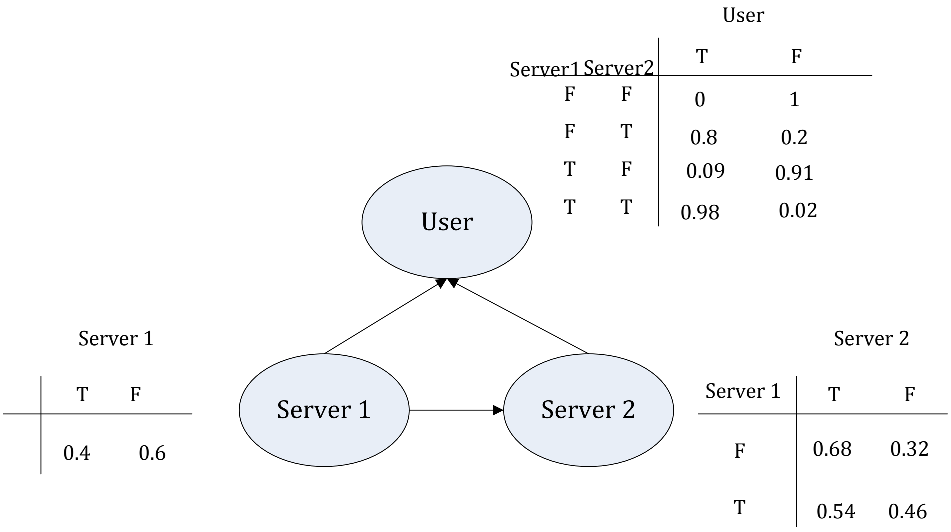
This step is to assign states for each variable. For simple considerations, a binary state indicating the true/false state is assigned to each variable. The following table shows the details of different variables.

Table7. Binary Condition of Example Variables

Variable	State	Meaning
User	T	User receives data packets
	F	User fails to receive data packets
Server1		
	T	Server 1 transmits data packets to user
	F	Server 1 fails to transmit data packets to user
Server 2	T	Server 2 transmits data packets to user
	F	Server 2 fails to transmit data packets to user

This step is to determine the probabilities for different variables. Considering this as an example, the original probabilities for parent variables are all assumed values. An original probability table is prepared for the parent variables and a conditional probability table is prepared for the child variable. See Figure 20.

Figure20. Probabilities of the Example BBN



Based on the above figure, the probability of sensor commanded fire can be determined.

$$P(Server1 = T \mid User = T) = \frac{P(User = T, Server1 = T)}{P(User = T)}$$
$$= \frac{(0.98 \times 0.54 \times 0.4 = 0.21168_{TTT}) + (0.09 \times 0.46 \times 0.4 = 0.01656_{TFT})}{0.21168_{TTT} + 0.01656_{TFT} + (0.8 \times 0.68 \times 0.6 = 0.3264_{TTF}) + 0_{TFF}}$$
$$= 0.4115 = 41.15\%$$

This conditional probability table is relatively small due to the fact of only two parent variables and all variables with only two states. Considering a real situation such as causal factors to accidents, a huge amount of variables would therefore be added with unlimited states.

6.2 APPLICATION OF BBN IN LIFEBOAT ACCIDENT ANALYSIS

Bayesian Belief Networks are often used to represent uncertainties in a probabilistic approach where the qualitative information is usually based on expert judgments. In another understanding, the human and organizational factors, for most of the times, are better fitted with BBNs because the HOFs are complex and uncertain. Studies on using BBNs in modeling the HOFs in maritime accidents were also made[22].

In general understanding, the Fault Tree Analysis (FTA) is a widely used method for dependability modeling and evaluation of technical problems. This technique is to identify an unwanted/undesired event as a Top Event (TE) and construct a hierarchical tree calling Fault Tree (FT) from events to the basic causes. There are some basic assumptions on the method:

Events should be binary, for example, working or not-working.

Events should be independent which means no interactions between different events.

Events and the next lower level causes should be connected by means of logical AND/OR gates.

It is not difficult to see that a significant number of accidents happened combined technical failure and human interference. Studies of mapping the FT and BBNs have shown a new perspective of analyzing such accidents[23]. In the report '*On the Use of the Hybrid Causal Logic Method in Offshore Risk Analysis*'[24], a framework which is called HCL framework in simple, combining the traditional risk analysis tools such as event trees, fault trees as well as BBNs has been developed to provide decision support for Norwegian oil and gas industry. Based on this article, a similar analysis can be proposed to the lifeboat accidents.

The initiating phase is to develop a fault tree/event tree structure for the specific accident. Then a decision must be made to decide events which need to be modeled in fault trees and further analyzed in details by using BBNs.

There are six steps presented in the article for adapting the HCL framework for the oil and gas industry.

Define Risk Influence Factors (RIFs) ad causal relationships for the relevant basic events of the fault trees.

The RIFs can be connected to another RIF or a binary event/node. In order to systemically combine the human and organizational factors as well as the causal relationships, expert judgments are essential.

Identify concurrent RIFs.

In this step, it should be noted that concurrent RIFs should be identified to be singular in the BBN to be constructed.

Build a BBN.

The article recommended that it should look like a wheel with the binary events on the outer edge and the structure of RIFs in the inner part.

Assign the conditional probability tables.

This method is presented in details in the next section.

Evaluate performance, and assign one state for (some of) the RIFs.

For simple consideration, a three state performance is used to replace the six state distribution of performance evaluation. See table 8 below.

Table8. States to Evaluate the RIFs

State	State Characteristics
1	State is better than reference level
0	Minimum intended safety level
-1	State is worse than minimum safety level

However, the analysts and decision makers must guarantee that the evaluation and assignment process is reliable when assigning the states.

Calculate the risk results.

In the report, the authors suggested an approximate approach for the calculation work. First, use a suitable software tool such as HUGIN, to model the BBN part. Then input the probabilities for binary states which are calculated above to the fault tree/event tree software such as Risk Spectrum.

6.3 ASSIGN CONDITIONAL PROBABILITY TABLES

This section will be divided into two parts which are separately 6.3.1 Conditional Probability tables for RIFs and 6.3.2 Conditional Probability tables for binary events.

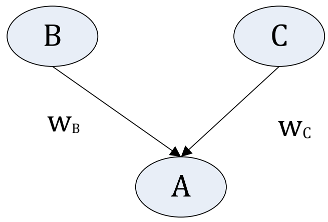
6.3.1 CONDITIONAL PROBABILITY TABLES FOR RIFS

For simple consideration, an example will be used to illustrate how to assign conditional probability tables for RIFs. Assume a simple structure such as Figure 21. Also assume all the variables have been properly defined and each of them has three states: +1, 0 and -1 which can be understood through Table 8. Under this condition, we only need to calculate 3^3 conditional probabilities for the child variable.

Figure21. A sample BBN for Calculating Conditional Probability Tables

P(B=1)	P(B=0)	P(B=-1)
0.6	0.3	0.1

P(C=1)	P(C=0)	P(C=-1)
0.5	0.3	0.2



B	C	
1	1	
1	0	
1	-1	
0	1	
0	0	To be determined
0	-1	
-1	1	
-1	0	
-1	-1	

There are three steps to determine the conditional probability table.

Step1. Weights Determination of Parent Variables B and C

This is based on the fact that the probability for a child variable that differs considerably from its parents' states should be small and on the contrary, there will be a greater probability for those who have a little or no deviation from its parents' states. The smaller probability should be assigned as well on condition that the greater deviation between parents' states.

Assume B has a greater effect than C. The importance measurement is based on the expert judgment and weighting meaning the sum of weight B and C should be 1. See Table 9.

Table9. Weights for Parent Variable B and C

	Factors determined by expert judgment	Normalized Weight
B	80%	W_B=0.8
C	20%	W_C=0.2

Step2. Distance Measurement of Parent Variables and Child Variable

This step is to calculate the distances from the RIF which in here means A to the parent variable B and C. The formula below is used to calculate the distance Z_j.

$$Z_j = \sum_{i=1}^{n} | Z_{ij} | w_i \,,\; Z_j \in [0,6]$$

-Z_{ij} here means the distance between the parent state *i* and the state of the RIF we are considering. For example, if we assume *j*=1, *i*=1 for B, the absolute value of Z_{ij} is |1-1|=0. Assume *j*=1, *i*=0 for C, the absolute value of Z_{ij} is |0-1|=1.

-*n* is the number of parents.

-*j* is a possible state of the RIF we are considering. In this example, *j* can be +1, 0 and -1.

-w_i is the weight of parent variable.

Assume B is in state 1 and C is in state 0, the distance measure for A, Z_1, Z_0 and Z_{-1} can be determined as follows:

$$Z_1 = | Z_{B1} | \times w_B + | Z_{C0} | \times w_C = 0 \times 0.8 + 1 \times 0.2 = 0.2$$

$$Z_0 = | Z_{B0} | \times w_B + | Z_{C0} | \times w_C = 1 \times 0.8 + 0 \times 0.2 = 0.8$$

$$Z_{-1} = | Z_{B-1} | \times w_B + | Z_{C-1} | \times w_C = | 1 - (-1) | \times 0.8 + | 0 - (-1) | \times 0.2 = 1.8$$

The rest distance measures from B, C to A is shown in the following table.

Table10. Distances from Parent Variable B and C to Child Variable A

B	C	Z_1	Z_0	Z_{-1}
1	1	0	1	2
1	0	0.2	0.8	1.8
1	-1	0.4	1	1.6
0	1	0.8	0.2	1.2
0	0	1	0	1
0	-1	1.2	0.2	0.8
-1	1	1.6	1	0.4
-1	0	1.8	0.8	0.2
-1	-1	2	1	0

Step3. Assign Probabilities for Z_j and Calculate Conditional Probability Table

Different Z_j should be assigned different probabilities. The probability distribution is determined by the following formula.

$$P_j = \frac{e^{-RZ_j}}{\sum_{j=a}^{f} e^{-RZ_j}}, \; P_j \in [0,1]$$

Here *R* means the outcome distribution index. Due to the negative sign in the index, it can be known that the higher R is, the lower probability the RIF is in a state distant from its parents' states. Here *a, f* should be considered to be changing from 1 to -1 via 0.

Still, *R* is not determined at all. The article assumed *R* is an intuitive index for experts. Based on the article, three default values of *R* (0,1and 2) is assigned to predict the probability distributions. See figure 22 for detailed calculation. It is able to be seen that it is a uniform distribution when *R*=0 and the greater *R* is, the narrower the probability distribution will be. Based on the expert judgment, *R*=1 will be assigned because it is believed to be the best to address the probability distribution of states A. Accordingly, a complete conditional probability table of state A is shown in table 11.

Figure22. Probability Distribution with 3 Default Values of R

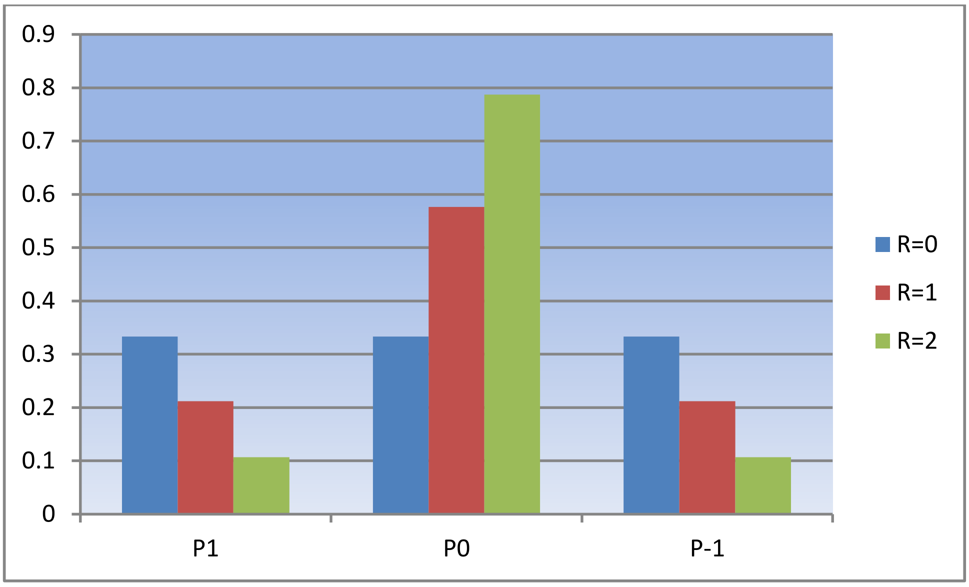


Table11. Conditional Probability Table for State A with R=1

B	C	P_1	P_0	P_{-1}
1	1	0.67	0.24	0.06
1	0	0.57	0.28	0.08
1	-1	0.54	0.23	0.09
0	1	0.29	0.39	0.13
0	0	0.21	0.42	0.16
0	-1	0.19	0.36	0.18
-1	1	0.16	0.18	0.25
-1	0	0.12	0.20	0.29
-1	-1	0.09	0.16	0.33

It can be seen that with a simple case, a large amount of dataset was constructed. For the real situation, analysis software will therefore be used.

6.3.2 CONDITIONAL PROBABILITY TABLE FOR BINARY STATES

For this step, the article also proposed three steps for the construction of conditional probability table based on the Barrier and Operational Risk Analysis (BORA) method.

Quantify basis probability. In most cases, it can be determined by using historical data.

Deterimne by expert judgement maximum deviation from the basis probability.

In this step, the adjustment factor reflecting the basis probability adjustment when parent variables in extreme states (-1 and 1) should be determined. The default state is in 0. A table is shown below for the selection of adjustment factors.

Table12. Adjustment Factors for Basis Probabilities

Parent RIFs state	Adjustment factors Q
-1	4[a]
0	1
1	0.55

a-The factors are only valid for basis probabilities p<0.1

Calculate the conditional probability tables. The conditional probability table are calculated as follows:

$$P_j = P_{basis}\sum_{i=1}^{n} w_i \sum_{k=1}^{-1} P_{ik} Q_{ik} \quad P_j \in [0,1]$$

P_{ik} are the probabilities for each parent variable *i* tobe in each state-1, 0 and 1. *Qik* would be the corresponding adjustment factors and w_i would be the weights for parents *i*. The index j are the possbile binary states (Failure or Working).

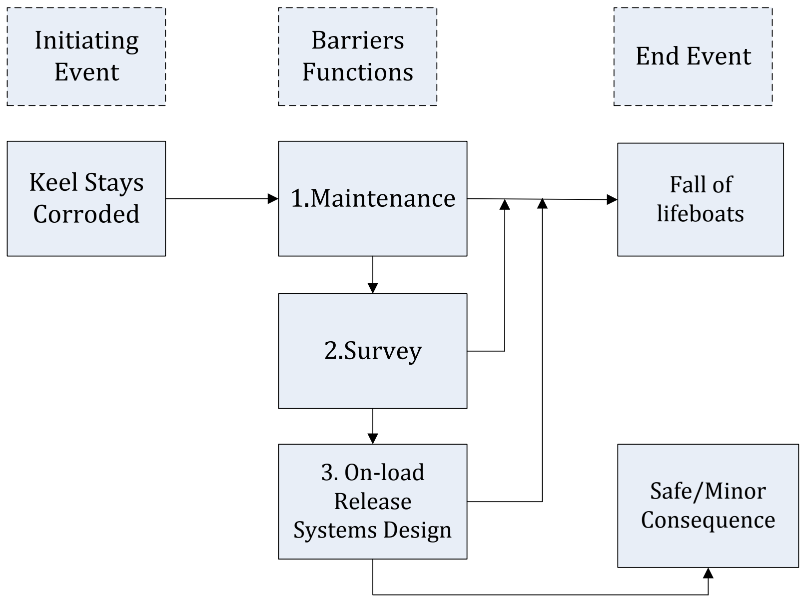
For example, assume the probability for parent event B is 0.2, 0.6 and 0.2 corresponding the state -1, 0 and 1, the probability for parent event C is 0.1, 0.7 and 0.2 corresponding the state -1, 0 and 1. The weights for B and C will be the 0.8 and 0.2. It is able to get the $P_{failure}$=1.45P_{basis}.

6.4 CASE STUDY OF BBN ON LIFEBOAT ACCIDENTS

In order to simplify the modeling work, a rather simple case 'Lowlands Grace' is used in this section. The accident analysis can be seen in the previous chapter 3 and 4 to help get a better understanding of the accident.

Based on the BORA method, a simple barrier block diagram is presented below. There are three barrier blocks to prevent the accident from happening. The first would be the maintenance regime for on-load release systems (keel stays are part of the systems). The following would be the survey regime for on-load systems. If both of the above fail and cause the releasing of lifeboat from one side, a robust design of on-load release systems would be able to function and prevent the release of lifeboat.

Figure23. Block Diagram for Lowlands Grace Lifeboat Accidents



The following steps will be based on section 6.2.

The first step is to define the RIFs and fault trees. The fault trees of lifeboat fall due to the maintenance and survey deficiencies are modeled in figure 24. It should be noted that the on-load release systems design is a basic event and therefore no fault tree for this event. The RIFs are defined in figure 25. The second step is to define concurrent RIFs. Here, the RIFs having the same description in figure 25 are considered to be concurrent. It should be noticed that *Time Pressure* factor and *Time* factor is different and should not be treated as the same. Based on the previous step a BBN can be built in step 3. See figure 26.

Figure24. Fault Trees for Barrier function 1 and 2

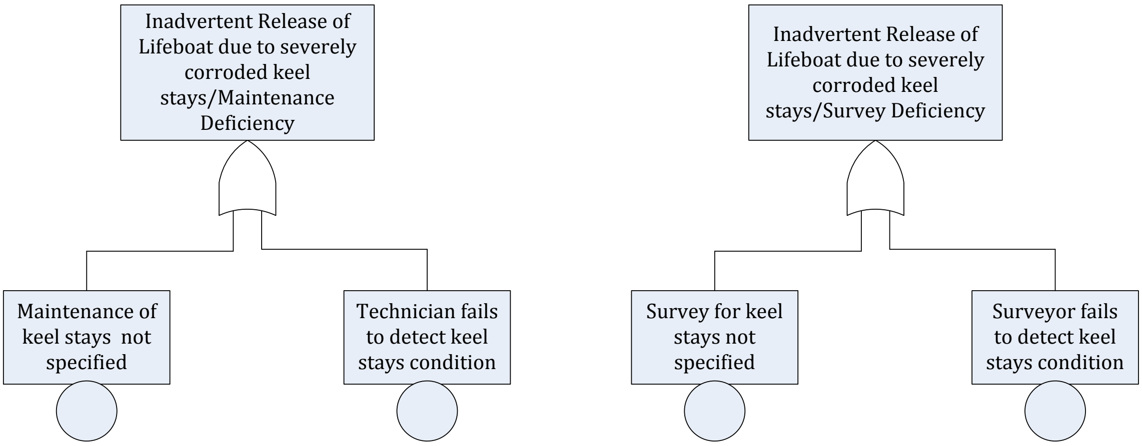
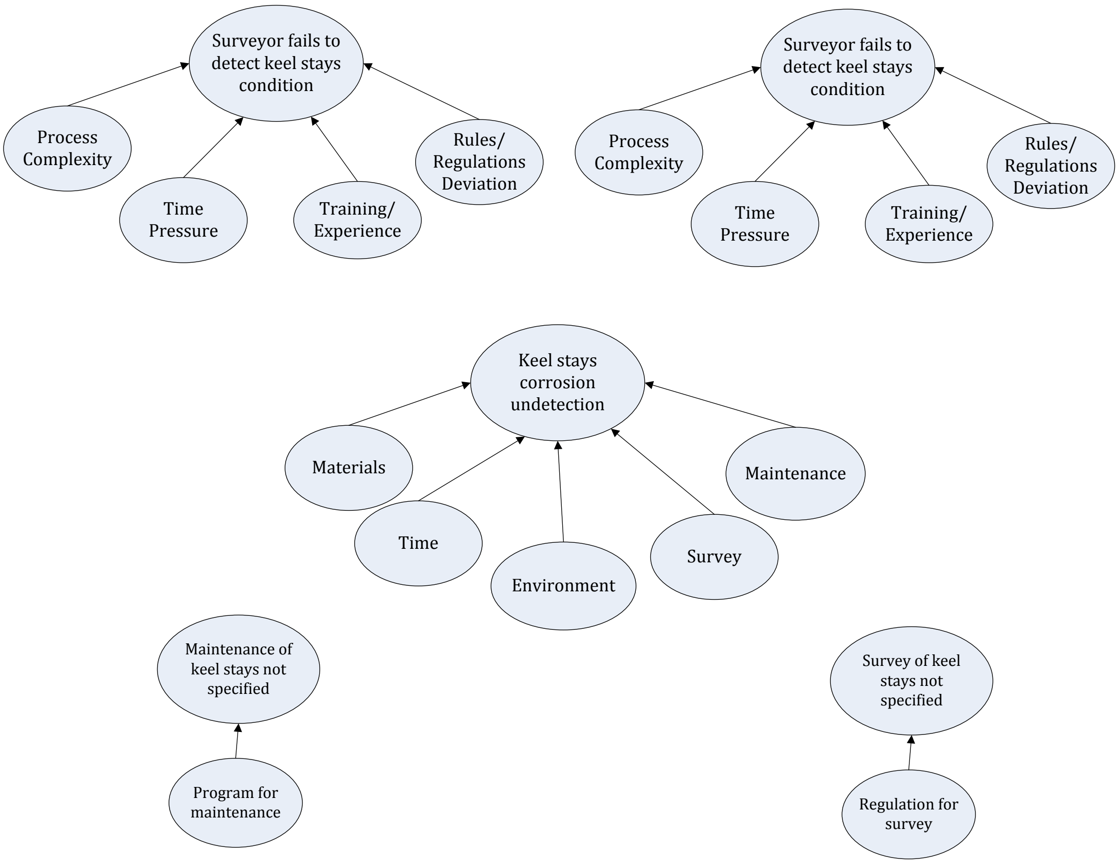
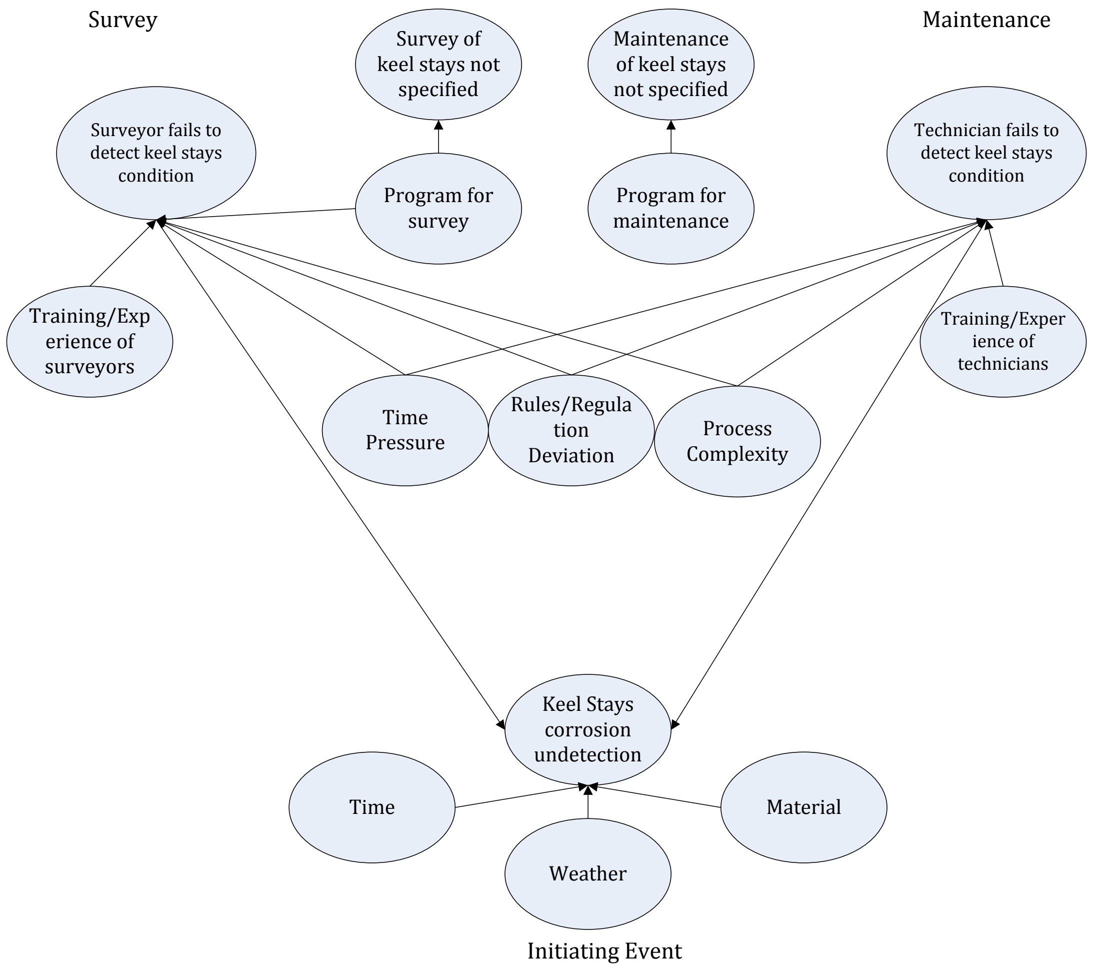


Figure25. Causal Relationship of Initiating Event and Basic Events for Fault Trees



The fourth step will be assigning the conditional probability tables. Here, only one example regarding the technician fails to detect the keel stays condition will be shown for the purpose of illustration. There will be totally 3^4=81 probabilities to be modeled if only 3 states are considered in this example.

Figure26. Bayesian Belief Network for the Specific Case



By using the method described above, the weights for parent factors will be firstly assigned. See table 13.

Table13. Weights for the Parent Factor of the RIF Technician 'Fails to Detect Keel Stays Condition'

RIF: Technician fails to detect keel stays condition	Factors assigned by expert judgment (%)	Normalized weights w_i
R: Rule/Regulation Deviation	50	0.46
C:Process complexity	30	0.27
E:Training/Experience of technician	20	0.18
T:Time pressure	10	0.09

Still, assume 3 states are separately -1, 0 and 1. Based on the distance measurement formula, the distance to the accident state (-1) can be determined. See appendix 2.

To determine the outcome distribution index R, expert judgments are needed. A value of 1 is determined due to the mild distribution curve in figure 22. Since the accidents have negative influences, the value of the child variable will be assigned to be -1. The conditional probability table is then determined. It can be read in the appendix 3. Detailed analysis such as most likely combination of states, probability of being at certain states given evidence, etc. can be performed in specific software such as HUGIN.

For determining the conditional probability of the binary state '*Maintenance of keel stays not specified*', the first step is to quantify a basis probability for the event. Due to the poor accident data, estimation will be made here. There were 266 investigated accidents listed in the appendix of Mr. T. W. Ross [25]. The estimated probability of this condition is 1/266=0.3%. The next step is to determine the maximum deviation from the basis probability by expert judgment. There is only one parent variable for this state and consequently the w_i is 1. Assume the probability distribution is 0.5 in -1, 0.2 in 0 and 0.3 in 1. Calculated

$$P_{failure} = 0.3\% \times (0.5 \times 4 + 0.2 \times 1 + 0.3 \times 0.55) = 0.71\%$$

Up to now, the conditional probability table has been constructed and BBN has been linked to the fault tree. Further analysis can also be made based upon the data.

CHAPTER 7 HUMAN FACTORS ANALYSIS

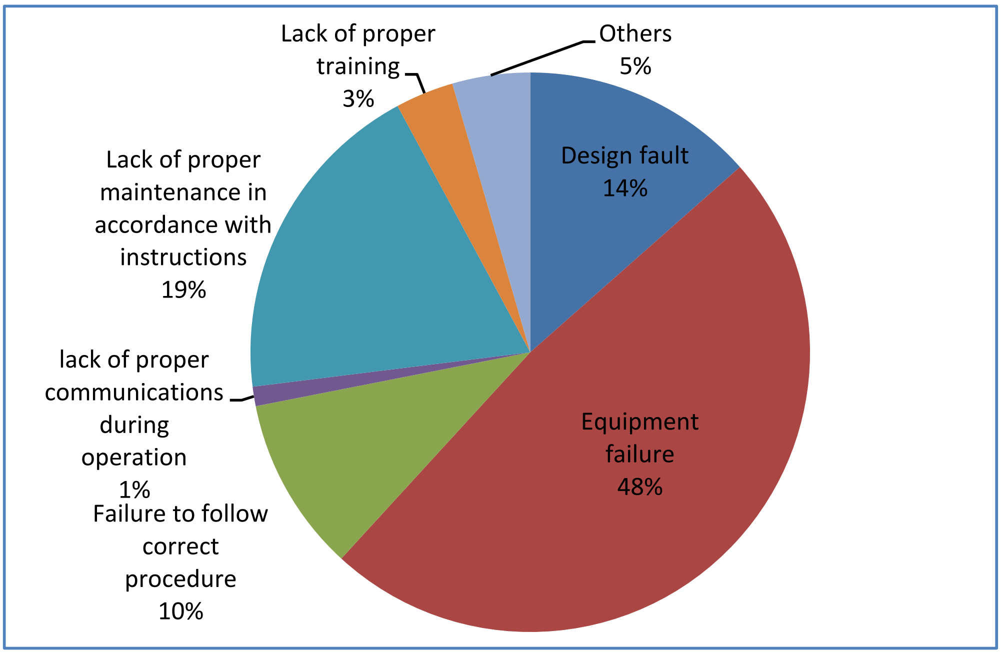
This chapter will address a modified framework based on the human factors analysis and classification system (HFACS) which was built for the aviation industry to investigate the role of human errors in lifeboat and its launching system accidents.

7.1 MOTIVATION FOR CONSTRUCTING HFACS FOR LIFEBOAT ACCIDENTS

Literatures indicated that human errors resulted in, or at least partly contributed to, the amount of 70%-80% aviation accidents. Thus, the human factors analysis and classification system (HFACS) was developed to investigate aviation accidents, basing on Reason's 'Swiss Cheese' model for latent and active failures [26]. It seemed the same case in maritime industry. Several studies also blamed on human errors as primary factor for a significant number of maritime accidents.

There was a joint survey of lifeboat incidents by OCIMF, INTERTANKO and SIGTTO at 2000. Among the 89 returned questionnaires, there are 30 incidents that can be attributed to the human errors, following the equipment failure. Human factors here consist of lack of proper training, lack of proper maintenance in accordance with instructions, lack of communications during operation and failure to follow correct procedure in Figure 24. Besides, the report also implied the indirect cause of accidents by human error in design. However, due to the fact that there is no case of lifeboat accidents happening under emergency, the evaluation of human factors contributing to lifeboat accidents would be unable to be performed. Among the published investigation reports, it is unable to see a human factors analysis.

Figure27. Primary Causes of Accidents of the Joint Survey by OCIMF, INTERTANKO and SIGTTO, 2000



One condition should also keep in mind that the lifeboat is supposed to be launched during emergency. In an emergency event, people's reactions could be different from person to person. In Svein's book [27], he mentioned that people who survived after an accident were experiencing common emergency reactions, ranging from panic to apathy and not willing to assist each other. The other issue could be the crowd-binding problem which was estimated to be affecting 6% passenger activities in a given situation, for instance in a passenger vessel. Another study he presented in his book addressed that around 10%-25% people could have strong psychic reaction and 1%-3% people might lose mental or nervous breakdown. From the seafarer's perspective, their behavior could be better after regular training.

From another stand-point, improving the reliability of survival equipment which is high enough for an operator to trust plus reducing the operation time especially under emergency could be effective ways of managing the personnel safety.

It can be understood from another point that there is requirement for improved design and higher reliability. Still, it can be seen from Figure 24 that human factor related accidents also take up a significant part with none happened during an emergency. This could be called for attention especially the qualification of seafarer's actions is under stricter rules and regulations nowadays.

Judging from above, there is need for a quantitative characterization of human errors relating lifeboat accidents. A HFACS for lifeboat accidents would be presented in the following section.

7.2 HFACS MODEL CONSTRUCTION

Originally, the HFACS is addressed in four hierarchical levels which a higher level will affect the lower level. The four levels are separately Unsafe Acts in Level 1, Preconditions for Unsafe Acts in Level 2, Unsafe Supervision in Level 3 and Organizational Influences in Level 4.

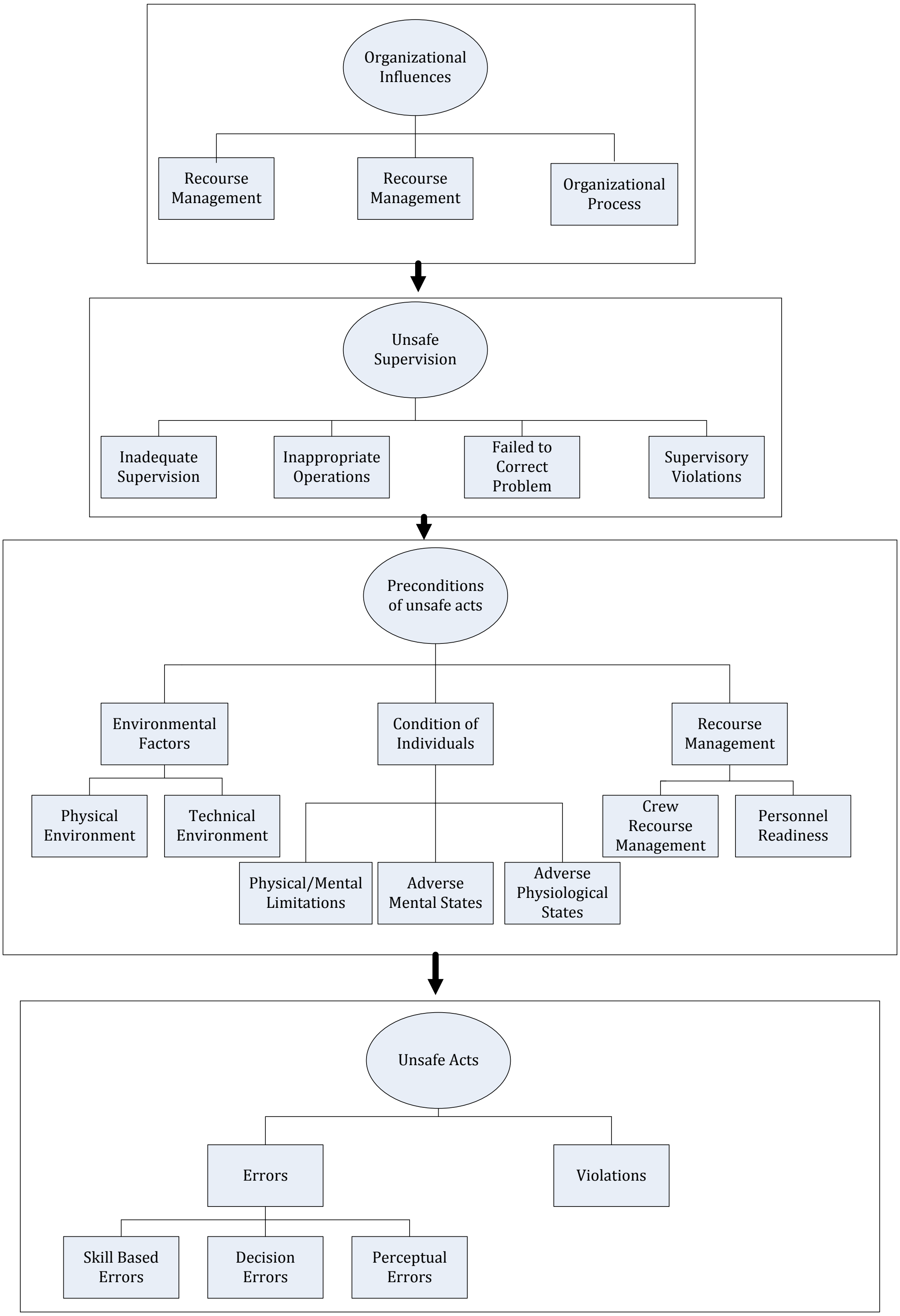
In the unsafe acts level, it can be classified into two categories: Errors and Violations. Errors can be subdivided into Decision-making errors; Skill based errors and Perceptual errors. Majority accident investigations were focused on this level. This is the level of personnel behaviors which were directly involved in the lifeboat operation. In order to understand the underlying factors that cause the unsafe acts, the preconditions of unsafe acts level is needed. It can be divided into three categories which are environmental factors, condition of individuals and personnel factors. Environmental factors include physical and technical environment factors. Conditions of individuals include physical/mental limitations, adverse mental states and adverse physiological states. Personnel factors include crew recourse management and personnel readiness. The causal factors can be traced back to the upper level- unsafe supervision which is consisted of inadequate supervision, inadequate operation, failed to correct a known problem and supervisory violations. The organizational influences consisting recourse management, organizational climate and organizational process show the latent failures and influence the lower level as described above. The overall diagram is shown in figure 25. The following table 14 shows some example human activities of total 4 levels. It should be noticed that not all activities are included.

Expert judgments should be made to deduce the probable causal factors of a higher level to the consequences in the lower level. The HFACS structure will be more useful if there is sufficient lifeboat accident data which can provide analysis support of the 4 hierarchical levels. In the same way, a better quantitative analysis of human and organizational factors could be performed by assisting Bayesian Belief Network.

Table14. Examples of Causal Factors in Different Levels

Level 1	Skill Based Errors	Poor Technique	Omitted warning item	Omitted step in procedure
	Decision Errors	Improper procedure	Wrong response to emergency	Poor decision
	Perceptual Errors	Visual illusion	Misjudged distance	
	Violations	Violated emergency rules	Not-qualified for the mission	
Level 2	Adverse Mental States	Complacency	Distraction	Mental fatigue
	Adverse Physiological States	Medical illness	Physiological incapacitation	
	Physical/Mental Limitation	Incompatible physical capacity	Insufficient reaction time	
	Crew Recourse Management	Failed to communicate	Failure of leadership	
	Personal Readiness	Self-medicating	Excessive physical training	
Level 3	Inadequate Supervision	Failed to provide guidance	Failed to track qualifications	Failed to provide training
	Inappropriate Operations	Mission not in accordance with rules/regulations	Improper manning	Failed to provide correct information
	Failed to Correct Problem	Failed to initiate corrective action	Failed to report unsafe tendencies	
	Supervisory Violations	Failed to enforce rules and regulations	Authorized unnecessary hazard	
Level 4	Resource Management	Human resources (selection, training, etc.)	Equipment/facility resources (poor design, unsuitable equipment, etc.)	
	Organizational Climate	Structure (Chain-of-command, Communication, etc.)	Policies (Hiring/firing, drugs and alcohol, etc.)	
		Culture Norms and rules, Values and beliefs, etc.)		
	Organizational Process	Operations (Time pressure, schedules, etc.)	Procedures (Standards, instructions, etc.)	Oversight(Risk management, safety programs)

Figure28. Human Factors Analysis and Classification System for Lifeboat Accidents



CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

This chapter will discuss the result from the previous chapters and propose some suggestions for further research.

8.1 RESULTS DISCUSSION

Even though lifeboat accident rates seem reduced today and less attention was paid compared to the previous years, it could still be dangerous and life-costing during drills and accident evacuation. So it is of importance to analyze lifeboat accidents to help improving lifeboat safety in an effective way.

In this report, case analysis was presented in the beginning and scenarios were identified. This provides the basic explanations on why lifeboat accidents happened. This objective was discussed based on the corresponding accident reports. Based on this point of breakthrough, the causal factors were defined. The defined causal factors formed the foundation of the subsequent research. Following, influence diagrams were constructed. This gave a systemic understanding of the causal factors by classifying them in different levels. It can be seen that there is similarity between the influence diagrams and the human factors analysis and classification system. A coding structure is then proposed specially for the lifeboat accidents from the technical and operational aspects. This helped the construction of BBN in the next chapter. In this coding structure, accesses were also provided to help further quantitative analysis. No such coding work had been done and this work could be seen as the first one. BBNs were built in the next step based on the hybrid causal factor method. Based on the classification system in the previous chapter, technical failures were analyzed through fault trees and operational failures were analyzed through BBN. With the data limitation, it can be seen that plentiful assumptions were made to simplify and assist the quantitative analysis. Still, it provided the data required for calculating the probability of a certain failure. Previous studies had looked at accident causes and consequences without giving probability estimations as well as the consideration of interacting events. This could also be regarded as the first application of BBN on lifeboat accidents. However, this research did not manage to demonstrate the overall picture of causal factors' probabilistic importance because of the time constraint and poor data size. Up to this step, it is able to build an analytical model for lifeboat accidents. After applying BBN on lifeboat accidents, an extra analysis of human and organizational factor was performed due to the reason that lifeboat operating heavily relies on people. It helps a systemic consideration of human and organizational factors in the lifeboat accidents.

8.2 FURTHER RECOMMENDATIONS

The study was restricted mainly by the recourses available and the limited time. Some suggestions are proposed for the future work.

- Coding work: This part is carried out based on the understanding of some accident reports and might be aspects which were omitted. A more correct structure will help a better coding of lifeboat accidents and provide useful information for the later work.
- Bayesian Network Development: Up to now, there is no available statistics on lifeboat accidents. Hence, no further lifeboat accident rates of different causal factors can be estimated. The causal relationships were only based on the subjective judgment. More detailed BBNs could be constructed assisting with

more variables. By realizing this, a better understanding of what actually are the dominating factors that influence the lifeboat safety could be determined.

- Variable States: For the simple calculation, variable states were restricted to only three conditions- negative, no influence and positive. In the actual case, results would be quite different if we adjust or add the variable states. As a fact of this, the 6 variable states which were mentioned in the reference article could be accepted. Concurrently, a higher requirement for coding the accident data.
- Quantitative Analysis of Human and Organizational Factors: The last chapter has already proposed a structure for classifying and analyzing human factors. Some of the researches also proposed different methods to give quantitative analysis of human factors. A similar study could also be conducted.

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APPENDIX

APPENDIX 1: DESCRIPTIONS OF PROBABLE FAILURE SEQUENCE OF LIFEBOAT ACCIDENTS

1.1 Lifeboat accident and fatalities of Hong Kong registered bulk carrier *Lowlands Grace*

On 7th Oct, 2004, the crews of bulk carrier Lowlands Grace were mustered at the port lifeboat station for a drill while the ship was anchored 11.7 miles north of Hunt Point, Port Hedland, in Western Australia.

There are totally 5 crews including the third mate, the fitter, an ordinary seaman, an able seaman and the third engineer. The third mate used the remote davit winch break cable inside the lifeboat to lower the boat. During the drill, the third mate halted the lowering process where the lifeboat was approximately 2-3m below the boat deck level and subsequently caused a momentary shock loads on the lifeboat's hooks. Because of the undetected corrosion of the lifeboat after hook's keel stays during routine maintenance and surveys, the load was strong enough to cause the keel stays to fail and separate from the keel block.

After the hook assembly failed, its operating cable was under tension and consequently unlocked the hook mechanism and caused the hook to open.

Due to the falling of the lifeboat's stern, it produced the downward momentum and thereby causing the fall of the lifeboat stern and the forward swing of the boat with simultaneously forward hook's rotating.

After rotating approx. 35 degrees with forward fall as pivot, the forward suspension ring contacted with the main pivot pin and from this point on, the open force on the forward hook mechanism was gradually increased with the further rotation of the lifeboat. When the lifeboat had rotated to be just in the vertical position, the foredeck failed due to the maximum dynamic load induced by the swinging boat.

With the lifeboat continuing rotating and swinging forward to approx. 220 degrees, the forward hook was subjected to increasing opening loads by the suspension ring acting as a lever. The forward hook's operating cable bulked and then the cam release pin rotated until the hook opened.

Since the lifeboat detached from both falls, it fell approx. 16m to the sea and caused accident and fatalities.

The keel attachments for hooks on lifeboats are therefore recommended to be inspected to ensure the strength. Because of the deficiencies of survey and maintenance regimes, it is recommended more thorough regimes for condition monitoring of the condition of lifeboat keel connection arrangements. The design company was also notified to review the design of the on-load release system.

1.2 *Lifeboat accident and injury to crew aboard the Panama flag bulk carrier Cape Kestrel*

The *Cape Kestrel* anchored around 16 miles north of Dampier in Western Australia to load a cargo of iron ore for China at 11 Oct. 2001. The next day, the master decided to take a lifeboat drill. However, due to the ship berthed port side to the wharf, the starboard lifeboat was to be lowered and tested.

Weather condition was good with little wind, calm sea and a low swell. Before starting the drill, the second engineer checked the starter panel for the davit winch, ensuring the power supply to the winch to hoist the boat on. The remote control that operated the winch was also checked and the indicator was lit indicating there was power when controlling the hoisting.

The mate, the third mate, the bosun, an ordinary seaman (OS) and the second engineer embarked the boat at the embarkation platform with all of them wearing helmet and a lifejacket. At around 0845 the mate used the remote control inside the lifeboat to lower the boat with the master watching from the bridge.

After the boat contacted with the water, the hooks were released. The lifeboat worked perfectly with engine running. Meanwhile, on board the ship, two seamen greased the falls and sheaves. After about half an hour the hooks were reconnected and secured in position.

An able-bodied seaman (AB) was standing by to recover the boat using the remote control unit for the winch motor. The AB pushed the hoist button under the recover command of the master, but nothing happened. The mate told the AB to inform 1st engineer of the problem when the boat was rolling in the swell and there was tension in the falls.

The first engineer went to the starter panel located in the air conditioning room for the winches. Then he saw that the circuit breaker had tripped. After resetting the circuit breaker, it tripped again when the AB tried the remote control. The 1st engineer then told the mate that the boat should be lifted manually.

Afterwards, the AB started to recover the boat using the winding handle. Because of the low recovering rate, the 1st discussed with the mate by radio and decided that there might be problems in the remote control. And then the AB stopped manually hoisting the boat. The 1st engineer asked the AB to notice any unusual sound from the winch motor which turned out to be no problem and nothing unusual.

The 1st engineer replied to the mate's request about why the hoisting was stopped and told him that he would hoist the boat from the lifeboat starter panel.

The 1st engineer asked the AB to notice him when the boat approaches the main deck. He then depressed the contractor in the winch motor starter box and started to hoist the boat.

The master informed the mate to ensure that everyone left the boat at the main deck. When the boat was at the main deck level, the 1st engineer heard a signal from the AB and stopped recovery of the boat by releasing the contractor. The mate now told the master that the boat was too far from the deck and added that the boat was designed so that the crews can embark and disembark at the boarding platform. The master then instructed the mate to use tackles to bowse the boat into the side of the ship. However, the mate expecting that the limit switches could operate to stop the winch before the cradles came up against the stops on the supporting frames, ignored the commands of the master and told the 1st engineer to continue the hoisting.

The master recalled that he thought the boat was coming in too fast and the limit switches did not seem to operate. The cradles reached the stops with the winch motor running and the forward falls parted. The boat hung vertically and soon the aft fall also parted. The boat fell about 20 meters, bow first, into the sea at around 0930.

Investigation showed that all ropes were heavily coated with grease which was in poor condition, discolored and with large amounts of hard particle contamination by visual inspection. The external strands were found to be extensively corroded varying along the length of the ropes with the most noticeably damaged regions in the location of failure after degreased.

The master was not aware that the first engineer had been using the contactor on the starter panel to hoist the boat and the limit switches had been bypassed. It is also indicated that the disembarkation at the main deck would not necessarily prevented the falls from parting whereas the injury to personnel would be prevented.

In the design philosophy of the control circuitry, the winch motor incorporates limit switches to stop the winch motor just short of the stowed position and prevent over-stressing of the wire falls. By manually actuating the contactor which bypasses the control circuitry, the protection against over-stressing of the falls, normally provided by the limit switches, were removed.

From the operation view, it is not clear but probable that the clutch lever which will affect the winch speed by the position change was not correctly positioned. The master's opinion was that the boat was coming too fast and the cradles went through the limit switches.

The first engineer was unaware that by operating the winch with the motor contactor, all the electrical safety interlocks to prevent damage to the davits and the boats, had been bypassed. The chief engineer who was already aware of the manner did not notice the first engineer that the boat should be stopped before the limit switches were contacted.

The mate realized disembarking at the main deck was not safe and ignored the master's strong protest. He told the 1st engineer to resume hoisting the boat while he did not seem to aware that the 1st engineer was not using the remote control to hoist it and even if he was aware, he was also not aware that the limit switches would not operate. The noise in the air conditioning room would have affected the 1st engineer hearing the mate on the radio. In fact, the 1st engineer claimed that he had been relying on the AB to tell him when to stop hoisting the boat. When not having received any such signal from the AB and not having aware the limit switches had been bypassed, the 1st engineer continued operating the contactor and then heard the davits hitting the stops and unusual noises.

1.3 Investigation into the lifeboat accident onboard the French registered Antarctic support vessel L'Astrolabe

In the investigation report published by ATSB, the 4-8 crew member of the French Antarctic support vessel *L'Astrolabe* was reported to be overboard at around local time 0400 and be deceased after his body was found at 0824 of 27th, Jan, 2005. The weather remained unchanged except the south-westerly swell height increased around 1.5m to 2m between the time of missing and recovery.

In order to keep the ship to head the swell, he maneuvered the ship from the helm position in the wheelhouse and thereby ignored observing the recovery operation. The mate drove the boat back to the port side of the supply ship and made several attempts from the astern of the falls hanging freely from the davits after they caught the 4-8 crew's body. The second mate was trying to grab the forward fall block and attach it to the forward fall hook on the lifeboat by leaning through the forward access hatch of the lifeboat. So was the second engineer at the aft end of the lifeboat. The falls were not attached to the lifeboat's forward painter after released. Because of the swell, the people at both ends of the lifeboat had difficulties in grabbing the fall blocks and then placing them on the lifeboat's hooks. The second engineer got his right hand caught between the block and hook assembly of the lifeboat when he tried to grab the swinging fall block at the 3rd time. His thumb of the right hand was almost severed. The second mate rushed to the aft and helped the engineer into the lifeboat. However, the lifeboat motion in the seaway was still unstable and it turned out to be difficult to attach the fall blocks to the hooks at both ends of the lifeboat. After about one hour of attempting, two painters were lowered from the supply ship to avoid the lifeboat collision with the ship. The falls were then raised a little and pulled closer to the ship by crews using boat hooks. Then they were lowered at a rate which is adequate for the crews in the lifeboat to attach the blocks to the hooks. The lifeboat was then recovered from the water. The whole operation took about 70 minutes. Investigations showed that the vessel's movement in the seaway made the lifeboat recovery difficult and resulted in damage to the lifeboat and its fittings. There are no 'hand holds' that attached to the suspension ring and the fall block which means the crew in the lifeboat had to manually attach the blocks and rings directly. It also indicated that if the lifeboats were required to equip the foul weather recovery strops, it would have prevented the danger of the swinging fall blocks to the lifeboat crews.

APPENDIX 2 DISTANCE MEASURE FOR CASE STUDY IN CHAPTER 6

R	C	E	T	Z_1	Z_0	Z_{-1}	R	C	E	T	Z_1	Z_0	Z_{-1}	R	C	E	T	Z_1	Z_0	Z_{-1}
1	1	1	1	0	1	2	0	1	1	1	0.46	0.54	1.54	-1	1	1	1	2.72	1	1.08
1	1	1	0	0.09	0.91	1.91	0	1	1	0	0.55	0.45	1.45	-1	1	1	0	2.81	0.91	0.99
1	1	1	-1	0.18	1	1.82	0	1	1	-1	0.64	0.54	1.36	-1	1	1	-1	2.9	1	0.9
1	1	0	1	0.18	0.82	1.82	0	1	0	1	0.64	0.36	1.36	-1	1	0	1	2.9	0.82	0.9
1	1	0	0	0.27	0.73	1.73	0	1	0	0	0.73	0.27	1.27	-1	1	0	0	2.99	0.73	0.81
1	1	0	-1	0.36	0.82	1.64	0	1	0	-1	0.82	0.36	1.18	-1	1	0	-1	3.08	0.82	0.72
1	1	-1	1	0.36	1	1.64	0	1	-1	1	0.82	0.54	1.18	-1	1	-1	1	3.08	1	0.72
1	1	-1	0	0.45	0.91	1.55	0	1	-1	0	0.91	0.45	1.09	-1	1	-1	0	3.17	0.91	0.63
1	1	-1	-1	0.54	1	1.46	0	1	-1	-1	1	0.54	1	-1	1	-1	-1	3.26	1	0.54
1	0	1	1	0.27	0.73	1.73	0	0	1	1	0.73	0.27	1.27	-1	0	1	1	2.99	0.73	0.81
1	0	1	0	0.36	0.64	1.64	0	0	1	0	0.82	0.18	1.18	-1	0	1	0	3.08	0.64	0.72
1	0	1	-1	0.45	0.73	1.55	0	0	1	-1	0.91	0.27	1.09	-1	0	1	-1	3.17	0.73	0.63
1	0	0	1	0.45	0.55	1.55	0	0	0	1	0.91	0.09	1.09	-1	0	0	1	3.17	0.55	0.63
1	0	0	0	0.54	0.46	1.46	0	0	0	0	1	0	1	-1	0	0	0	3.26	0.46	0.54
1	0	0	-1	0.63	0.55	1.37	0	0	0	-1	1.09	0.09	0.91	-1	0	0	-1	3.35	0.55	0.45
1	0	-1	1	0.63	0.73	1.37	0	0	-1	1	1.09	0.27	0.91	-1	0	-1	1	3.35	0.73	0.45
1	0	-1	0	0.72	0.64	1.28	0	0	-1	0	1.18	0.18	0.82	-1	0	-1	0	3.44	0.64	0.36
1	0	-1	-1	0.81	0.73	1.19	0	0	-1	-1	1.27	0.27	0.73	-1	0	-1	-1	3.53	0.73	0.27
1	-1	1	1	0.54	1	1.46	0	-1	1	1	1	0.54	1	-1	-1	1	1	3.26	1	0.54
1	-1	1	0	0.63	0.91	1.37	0	-1	1	0	1.09	0.45	0.91	-1	-1	1	0	3.35	0.91	0.45
1	-1	1	-1	0.72	1	1.28	0	-1	1	-1	1.18	0.54	0.82	-1	-1	1	-1	3.44	1	0.36
1	-1	0	1	0.72	0.82	1.28	0	-1	0	1	1.18	0.36	0.82	-1	-1	0	1	3.44	0.82	0.36
1	-1	0	0	0.81	0.73	1.19	0	-1	0	0	1.27	0.27	0.73	-1	-1	0	0	3.53	0.73	0.27
1	-1	0	-1	0.9	0.82	1.1	0	-1	0	-1	1.36	0.36	0.64	-1	-1	0	-1	3.62	0.82	0.18
1	-1	-1	1	0.9	1	1.1	0	-1	-1	1	1.36	0.54	0.64	-1	-1	-1	1	3.62	1	0.18
1	-1	-1	0	0.99	0.91	1.01	0	-1	-1	0	1.45	0.45	0.55	-1	-1	-1	0	3.71	0.91	0.09

1	-1	-1	-1	1.08	1	0.92	0	-1	-1	-1	1.54	0.54	0.46	-1	-1	-1	-1	3.8	1	0

RIF: Technician fails to detect keel stays condition	Factors assigned by expert judgment (%)	Normalized weights w_i
R: Rule/Regulation Deviation	50	0.45
C:Process complexity	30	0.27
E:Training/Experience of technician	20	0.18
T:Time pressure	10	0.09

APPENDIX 3 CONDITIONAL PROBABILITY TABLE FOR CASE STUDY IN CHAPTER 6

R	C	E	T	P_{-1}	R	C	E	T	P_{-1}	R	C	E	T	P_{-1}
1	1	1	1	0.09	0	1	1	1	0.09	-1	1	1	1	0.44
1	1	1	0	0.10	0	1	1	0	0.09	-1	1	1	0	0.45
1	1	1	-1	0.12	0	1	1	-1	0.09	-1	1	1	-1	0.49
1	1	0	1	0.11	0	1	0	1	0.09	-1	1	0	1	0.45
1	1	0	0	0.12	0	1	0	0	0.09	-1	1	0	0	0.46
1	1	0	-1	0.15	0	1	0	-1	0.09	-1	1	0	-1	0.50
1	1	-1	1	0.15	0	1	-1	1	0.10	-1	1	-1	1	0.54
1	1	-1	0	0.17	0	1	-1	0	0.10	-1	1	-1	0	0.55
1	1	-1	-1	0.20	0	1	-1	-1	0.10	-1	1	-1	-1	0.59
1	0	1	1	0.12	0	0	1	1	0.09	-1	0	1	1	0.46
1	0	1	0	0.14	0	0	1	0	0.09	-1	0	1	0	0.46
1	0	1	-1	0.16	0	0	1	-1	0.09	-1	0	1	-1	0.50
1	0	0	1	0.15	0	0	0	1	0.09	-1	0	0	1	0.46
1	0	0	0	0.16	0	0	0	0	0.09	-1	0	0	0	0.47
1	0	0	-1	0.19	0	0	0	-1	0.09	-1	0	0	-1	0.51
1	0	-1	1	0.20	0	0	-1	1	0.10	-1	0	-1	1	0.55
1	0	-1	0	0.22	0	0	-1	0	0.10	-1	0	-1	0	0.56
1	0	-1	-1	0.25	0	0	-1	-1	0.10	-1	0	-1	-1	0.60
1	-1	1	1	0.20	0	-1	1	1	0.10	-1	-1	1	1	0.59
1	-1	1	0	0.21	0	-1	1	0	0.10	-1	-1	1	0	0.59
1	-1	1	-1	0.25	0	-1	1	-1	0.10	-1	-1	1	-1	0.64
1	-1	0	1	0.23	0	-1	0	1	0.10	-1	-1	0	1	0.60
1	-1	0	0	0.25	0	-1	0	0	0.10	-1	-1	0	0	0.60
1	-1	0	-1	0.28	0	-1	0	-1	0.10	-1	-1	0	-1	0.64
1	-1	-1	1	0.30	0	-1	-1	1	0.11	-1	-1	-1	1	0.68
1	-1	-1	0	0.32	0	-1	-1	0	0.11	-1	-1	-1	0	0.68
1	-1	-1	-1	0.36	0	-1	-1	-1	0.11	-1	-1	-1	-1	0.72