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FORMAL SAFETY ASSESSMENT OF FISHING VESSELS

By

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Accident Sub-Category	Generic Location				
	Berth	Harbour	Coastal	At sea	Dry dock
Engine room	F5 S1 (5)	F5 S2 (6)	F5 S3 (7)	....	.....
Bridge	F1 S2 (2)	F1 S3 (3)	....	....	.....
Cargo Hold	.	.	....	....	.

Table 4.3 Example of a risk table

4.3.4 "Equivalent Total"

The purpose for calculating the "Equivalent Total" is to provide a means of integrating the risks evaluated for each hazard of the accident sub-category. It will also provide a means of comparing each accident category to determine and justify the allocation of resources - to eliminate or reduce the level of risk.

Table 4.4 represents an example for a fire accident category. The data has been drawn from MAIB reports and Tables 4.1 and 4.2 are used to assign the values of S and F respectively. A RRN is assigned for each accident sub-category at different generic locations. This table can be generated for each accident category by analysing the incident/accident data in terms of its recurrence and severity of consequences.

Accident Sub-Category	Berthing/ Unberthing	Manoeuvring (Harbour)	At sea (Coastal)	At sea (Open sea)	Dry dock Maintenance
Fish Room Space	F4 S1=4	F4 S2 = 5	F4 S3 = 6	F4 S3 = 6	F4 S1 = 4
Galley	F4 S1 = 4	F4 S2 = 5	F4 S3 = 6	F4 S4 = 7	F4 S1 = 4
Crew Accommodation	F4 S2 = 5	F4 S2 = 5	F4 S3 = 6	F4 S3 = 6	F4 S1 = 4
Bridge	F3 S1 = 3	F3 S1 = 3	F3 S1 = 3	F3 S1 =3	F3 S1 = 3
Engine Room	F5 S1 = 5	F5 S2 = 6	F5 S3 = 7	F5 S3 = 7	F5 S2 = 6

Table 4.4 Fire rankings using Risk Matrix Approach- expert judgement

Table 4.5 shows the number of times each RRN appears within an accident category. For example, RRN 4 appears 5 times (as highlighted in table 4.4). As the RRN for the accident sub-category is considered for different generic locations. an "Equivalent Total" is calculated to give the accident category an index which will later be used to compare and rank it against other accident categories.

RRN	*No. of occurrence for accident. sub category*
4	5
5	5
6	7
7	3

Table 4.5. Number of occurrences of risk ranking scores

The calculation makes use of the fact that both the frequency and severity bands of the risk matrix are approximately logarithmic (e.g. a risk level of 6 is treated as 10^6) [MSC, 1997b]. Using 7 as a base then:

"Equivalent Total" = 7 + Log (3.000 + 0.700 + 0/050 + 0.005)
= 7+ Log (3.755)
= 7.57

Alternatively using the risk ranking score of 4 as the base, then:

“Equivalent Total” = 4 + Log (3000 + 700 + 40 + 5)
= 4 + Log (3755)
= 7.57 or rounded off = **7.6**

It can be noted that the risk ranking score does not change with the base chosen. Similarly, for each accident category an "Equivalent Total" can be calculated and the value obtained will give a direct indication of the areas needing attention. The higher the value of the 'equivalent total', the higher the associated risk with reference to that category.

4.3.5 Recommendations

For particular risk factors, there is a range of risk control options (RCO). It is most cost effective to reduce risk factors at the design stage. Additional costs are incurred in redesigning or modifying plant or processes once they are being used. However, redesigning a fishing vessel or related systems - as an alternative RCO could prove useful for new vessels. Hence, this option should be considered while carrying out a safety assessment for existing ships.

The various objectives and attributes of a RCO are discussed in section 4.2.3. At this stage, practical RCOs are recommended while considering the effectiveness of each option. The RCO could be in the form of a preventive measure - where the RCO reduces the probability of occurrence, or a mitigating measure - where the RCO reduces the severity of the consequences. Other factors that need to be considered are the cost of the RCO and the stakeholders who will be affected by its implementations.

Stakeholders can be defined to be any entity (e.g. person, organisation, company, nation state or grouping of these), who is directly affected by accidents or by the cost effectiveness of the industry. For any particular stakeholder, their stake in a generic vessel can be a definite committed monetary value such as an investment or payment. Stakeholders can be voluntary, involuntary or a mixture of both. In the decision making process, the stakeholders may be affected directly, indirectly or by representative groupings. The following stakeholders are identified for a generic fishing vessel:

- Crew
- Coastal state
- Designer/constructor
- Classification society
- Owner
- Port authority
- Port state
- Other vessels
- Flag state
- Insurance companies
- Emergency services
- Suppliers

The next step of the proposed method is to determine the best RCO for the identified risks of the generic vessel. This could be achieved by determining the cost and benefit of each RCO with respect to each of the stakeholders mentioned above. Each RCO can then be represented by a Cost per Unit Risk Reduction (CURR). The CURR is given by:

$$CURR = \frac{Cost - Benefit}{Risk\ reduction} \qquad (1)$$

The cost and benefit for each RCO has to be calculated in terms of its Net Present Value (NPV). Hence the numerator in equation (1) is represented as:

$$NPV = \sum_{t=0}^{n} \left[(C_t - B_t)(1+r)^{-t} \right] \qquad (2)$$

where B = the sum of benefits in period t

C = the sum of costs in period t

r = the discount rate

t = time horizon for the assessment, starting in year 0.

The risk reduction is given by the difference between the risk level of the given event in the base case and the risk level of the given event following the adoption of the RCO. A negative CURR suggests that implementation would be a financially beneficial (cost-effective). All that is left now, is to rank the RCOs using their CURR value and recommending the most appropriate RCO for an accident category.

4.4 An Example

The example presented in this section is for a generic fishing vessel as defined in section 4.3.1. The information gathered for the accident category and sub-category in section 4.3.2 is used to demonstrate the proposed method. For the purpose of this demonstration, only three accident categories are considered, namely, collision/contact, fire and loss of hull integrity. Using the accident data provided in chapter 2, by the MAIB reports and complementing this data with expert judgement - where the data was absent or incomplete, tables 4.6, 4.7 and 4.8 are generated. Expert judgements were drawn from ship owners and operators during a round table discussion. These tables represent the evaluation of the three accident categories identified. The RRN definition and interpretation of the values for frequency of occurrence are given in tables 4.1 and 4.2 respectively.

Accident Sub-category	Generic Location				
	Berthing/ Unberthing	Manoeuvring (Harbour)	At sea (Coastal)	At sea (Open sea)	Dry dock Maintenance
Berthed	F3 S2 (4)				
Loading/ unloading	F4 S2 (5)				
Departure	F5 S2 (6)				
Manoeuvring		F5 S2 (6)			
Passage open sea				F4 S3 (6)	
Loading fish at sea				F6 S3 (8)	
Entering harbour		F5 S2 (6)			
Manoeuvring close to berth	F5 S2 (6)				
Shutdown	F4 S2 (5)				
Abnormal operation	F4 S2 (5)	F4 S2 (5)	F4 S3 (6)	F4 S3 (6)	F4 S1 (4)
Maintenance					F3 S1 (3)
Anchored	F5 S2 (6)				
Dry docked					F4 S1 (4)

Table 4.6 Collision/contact risk ranking

Accident Sub-category	Generic Location				
	Berthing/ Unberthing	Manoeuvring (Harbour)	At sea (Coastal)	At sea (Open sea)	Dry dock Maintenance
Fish room space	F4 S1 (4)	F4 S2 (5)	F4 S3 (6)	F4 S3 (6)	F4 S1 (4)
Galley	F4 S1 (4)	F4 S2 (5)	F4 S3 (6)	F4 S4 (7)	F4 S1 (4)
Crew accomm.	F4 S2 (5)	F4 S2 (5)	F4 S3 (6)	F4 S3 (6)	F4 S1 (4)
Bridge	F3 S1 (3)	F3 S1 (3)	F3 S1 (3)	F3 S1 (3)	F3 S1 (3)
Engine room	F5 S1 (5)	F5 S2 (6)	F5 S3 (7)	F5 S3 (7)	F5 S2 (6)

Table 4.7 Fire risk ranking

Accident Sub-category	Generic Location				
	Berthing/ Unberthing	Manoeuvring (Harbour)	At sea (Coastal)	At sea (Open sea)	Dry dock Maintenance
Hull plating	F3 S1 (3)	F3 S2 (4)	F3 S2 (4)	F3 S2 (4)	F3 S1 (3)
Framing	F3 S1 (3)	F3 S2 (4)	F3 S2 (4)	F3 S2 (4)	F3 S1 (3)
Bulkheads	F3 S1 (3)	F3 S2 (4)	F3 S2 (4)	F3 S3 (5)	F3 S1 (3)
Welds and joints	F4 S1 (4)	F3 S2 (4)	F4 S2 (5)	F4 S2 (5)	F4 S1 (4)
Penetrations	F5 S1 (5)	F5 S1 (5)	F5 S2 (6)	F5 S2 (6)	F5 S1 (5)
Seals	F5 S1 (5)	F5 S1 (5)	F5 S1 (5)	F5 S1 (5)	F5 S1 (5)
Appurtenances	F4 S1 (4)	F4 S2 (5)	F4 S2 (5)	F4 S3 (6)	F4 S1 (4)
Doors	F4 S1 (4)	F4 S2 (5)	F4 S2 (5)	F4 S3 (6)	F4 S1 (4)
Windows	F4 S1 (4)	F4 S1 (4)	F4 S2 (5)	F4 S2 (5)	F4 S1 (4)

Table 4.8 Loss of hull integrity risk ranking

In order to calculate the "Equivalent Total", the number of occurrence of each ranking score for the three accident categories is determined and summarised here in table 4.9.

RRN	***No. of occurrence for accident category***		
	Collision/contacts	Fire	Loss of hull integrity
4	3	5	18
5	4	5	17
6	8	7	4
7	-	3	-
8	1	-	-

Table 4.9 Number of occurrence of each ranking score (three accident categories)

Using 4 as the base score, the "Equivalent Total" for accident category collision/contact is given by:

$$EquivalentTotal = 4 + \log(10843) = 8.0351$$

Using 4 as the base score, the "Equivalent Total" for accident category fire is given by:

$$EquivalentTotal = 4 + \log(3755) = 7.574$$

Using 4 as the base score, the "Equivalent Total" for accident category loss of hull integrity given by:

$$\begin{aligned} EquivalentTotal &= 4 + \log(400 + 170 + 18) \\ &= 4 + \log(588) \\ &= 6.769 \end{aligned}$$

The result of this analysis is presented in a tabular format to enable easy reading and is given in table 4.10. A larger risk ranking number ("Equivalent Total") indicates a high risk, but the values only represent the relative risk levels. Hence, this ranking gives an indication as to which areas of the generic vessel are of higher priority.

Accident category	*Collision/contact*	*Fire*	*Loss of hull integrity*
Equivalent Total	**8.035**	**7.574**	**6.769**

Table 4.10 Summary of analysis

The next step of the analysis is to determine the possible RCOs for the generic vessel considered. As data to quantify each RCO is difficult to obtain, hypothetical RCOs are considered for the demonstration of this method. The cost and benefit column represent the cumulative values for all the stakeholders involved in the study. The views presented by each stakeholder, will considerably affect the outcome of the CURR. Considering the four RCOs given in table 4.11 and the associated cost, benefit and risk reduction, a CURR for each RCO can be obtained. Note that the value for risk reduction represents the total number of equivalent deaths for the system under consideration.

Risk Control Options	Cost	Benefit	Risk reduction
RCO 1	£50000	£25000	5
RCO 2	£10000	£25000	5
RCO 3	£10000	£15000	5
RCO 4	£30000	£40000	5

Table 4.11 RCOs determined for generic vessel

Assuming that the time horizon for the safety assessment is for 25 years at a discount rate of 3%, and using equation (1) and (2) in section 4.3.5, the CURR calculation for each RCO is given as follows:

$$CURR_1 = \frac{(50000 - 25000)(1+0.03)^{-25}}{5} = 2388.02$$

$$CURR_2 = \frac{(10000 - 25000)(1+0.03)^{-25}}{5} = -1432.08$$

$$CURR_3 = \frac{(10000-15000)(1+0.03)^{-25}}{5} = -796.00$$

$$CURR_4 = \frac{(30000-40000)(1+0.03)^{-25}}{5} = -955.21$$

A large negative CURR suggests that this implementation would be financially beneficial. From the results obtained, it is determined that RCO 2 is the best option (from a cost-benefit point of view) and can be recommended for implementation.

4.5 Conclusion

It should be noted that the FSA approach differs significantly from the safety case regimes found in many industries. The main intention of FSA (during the development stages of the approach) was to be applied to the regulatory regime for shipping. However, over the years, its potential has been recognised not only as a tool to develop safety rules and regulations but as a tool to identify safety related problems with design, operation and procedures of a maritime entity.

The FSA method has several benefits to offer the fishing vessel industry, these benefits are summarised here:

- FSA provides a consistent regime that addresses all aspects of safety (design and operation) in an integrated manner.
- FSA is a pro-active approach. Hence, it enables hazards that have not yet given rise to accidents to be properly considered.
- Owners and operators can rest assure that safety investments are targeted where it will achieve the greatest benefit.
- It provides a rational basis for addressing new risks posed by the changes in marine technology.

This chapter has described a trial application of the proposed FSA technique for a generic fishing vessel. Several problems have been identified with the use of the current method as proposed by the MCA to the IMO, these include:

- Reliable data is not available for fishing vessels - and when it is available, there is a high level of uncertainty associated with the data.
- The risk matrix approach is a simple subjective method to quantify the probability of occurrence and severity of the associated consequences, however, it lacks a formal approach to quantifying expert judgement and opinion when using the risk matrix. This would entail that conflicting opinions of two different analysts on the severity of an accident could result in a deadlock.
- It is difficult to quantify the cost and benefits of each RCO for each of the identified stakeholders. A more subjective approach is needed to express the preference of one RCO over the other.
- Human reliability can be considered in the FSA methodology, however, quantification may be impractical due to the lack of human reliability data associated with maritime tasks. As such there is a need to address this problem using a formal subjective approach.

The setbacks of the FSA methodology identified here are addressed by the development of various methods that are presented in the following chapters of this thesis. The interaction of the proposed FSA framework and the parts developed in this thesis can be seen in figure 4.4.

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Abbreviations

AHP	Analytical Hierarchy Processing
ALARP	As Low As Reasonably Possible
ARM	Availability Reliability and Maintainability
ASEP	Accident Sequence Evaluation Programme
BRM	Boolean Representation Method
CBA	Cost Benefit Assessment
CCA	Cause-Consequence Analysis
CIL	Critical Item List
CM	Condition Monitoring
COGENT	Cognitive Event Tree
CURR	Cost per Unit Risk Reduction
DA	Diagraph-based Analysis
DETR	Department of the Environment, Transport and the Regions
DNV	Det Norske Veritas
DTA	Delay Time Analysis
EPIRB	Emergency Position Indicating Radio Beacon
ETA	Event tree Analysis
FAO	Food and Agricultural Organisation
FAR	Fatal Accident Rate
FISG	Fishing Industry Safety Group
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Assessment
FN curve	Frequency and Number of fatality curve
FSA	Formal Safety Assessment
FST	Fuzzy Set Theory
FT	Fault Tree
FTA	Fault Tree Analysis

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CHAPTER 5

RISK ASSESSMENT USING FUZZY SET APPROACH

Summary

The failure data available for fishing vessels are scarce and often accompanied with a high degree of uncertainty. For this reason the use of conventional probabilistic risk assessment methods may not be well suited. In this chapter a proposed method using Fuzzy Set Theory (FST) to model the occurrence likelihood and consequences of the identified hazards on a fishing vessel is presented. The different ways uncertainties can manifest in an analysis are discussed and this is followed by a review of FST, identifying the various applications of the theory in the past. The proposed method uses fault tree analysis to calculate the fuzzy probability of the system failure. The consequences of failure for each basic event within the fault tree are considered for four different categories. The risk of the basic events is determined by combining the likelihood of occurrence and consequences of failure in linguistic terms and is further defuzzified to produce a risk ranking. The application of this method is demonstrated using a hydraulic winch operating system of a fishing vessel.

5.1 Introduction

Where a major decision regarding cost or safety implication has to be made, it has become increasingly difficult to defend the traditional qualitative process called "engineering judgement". Thus, there has been a steady trend towards quantifying risks and/or costs, in particular the techniques of HAZard IDentification (HAZID), Quantitative Risk Assessment (QRA) and Cost-Benefit Analysis (CBA), have come very much to the fore.

QRA is a process of investigating potential accidents and expressing the results in terms of measures that reflect both the frequency and the potential loss severity of each type of accident that can occur [Henley E.J. and Kumamoto H., 1992]. The measures in most common use are Potential Loss of Life per annum (PLL)[1], Fatal Accident Rate (FAR)[2], Individual Risk Per Annum (IRPA)[3] and the FN curve[4].

Upon identifying the list of potential hazards and its contributing factors, which could be achieved by several methods including HAZard and OPerability studies (HAZOP) [Villemeur A., 1992], Failure Mode and Effects Analysis (FMEA) [MIL-STD 1629A], Fault Tree Analysis (FTA) [Henley E.J. and Kumamoto H., 1992] etc, the next step is to quantify these events for the risk estimation phase. Quantification of risk considers two parameters, namely,

1. Probability of failure event occurrence.
2. Consequence severity.

These are the two parameters that are considered in many risk assessments utilised by the industry at present [Preyss C., 1995]. Risk is defined to refer to a probability distribution over a set of outcomes [Banard R.C., 1996]. When the outcomes in question are hazards or injuries, risk can be understood to refer to different potential severity of hazards or injuries.

The frequencies of hazardous events are usually based on historical failure data. Often, little is known of the basis of the data or its processing and interpretation. The little that is known often raises doubts as to its quality, completeness and relevance. In the case of data relating to material or equipment failure, the attributes of the material or equipment are often not recorded and insufficient data is given in the context of its use. Almost invariably, failures are assumed to be random in time, that is, an observed number of failures is divided by an exposure period to give an annual failure rate and this is assumed to be age-independent. In reality, some modes of failure are more common in the earlier or later years of the life of a component or a system (application of the 'bathtub' curve). Even where data is of high quality, sample sizes are often small and statistical uncertainties are correspondingly large. As such, a fuzzy set modelling

[1] The estimated number of fatalities over a given future period of time.
[2] The number of fatalities per 100Mh of exposure to a particular hazard.
[3] The estimated probability per year of a particular member of the workforce being killed in an accidental event.
[4] A graph displaying frequency F of events killing N or more people (a societal risk measure).

approach may be more appropriate to model the probability of a hazardous event occurring.

The quantification of severity can be accomplished in several ways, subjective reasoning and expert judgement is one of the common methods. As accidents on fishing vessels are rarely reported, it may be difficult to quantify the severity of an accident. Once again, the use of a fuzzy set modelling approach integrating expert knowledge is well suited for this purpose.

Many fishing companies in the UK have very poor organisational structure and most are skipper owned vessels. This would entail that documented records on vessel, system and component would be difficult to come by and the availability of data for quantitative analysis is either unavailable or far from the ideal format. This has led to the need of developing a risk assessment method that could address the high level of uncertainty in the data.

5.2 Uncertainty

There is a close relationship between complexity and uncertainty and it is said that as the complexity increases, certainty decreases [Friedlob G.T. and Schleifer L.L.F., 1999]. Albert Einstein said that so far as mathematics refers to reality, it is not certain, and so far as mathematics is certain, it does not refer to reality [McNeill D. and Freiberger P., 1993]. In his "Law of Incompatibility", Zadeh states "As complexity rises, precise statements lose meaning, and meaningful statements lose precision" [McNeill D. and Freiberger P., 1993]. In 1965, while pondering this loss of precision, Zadeh conceived the notion of fuzzy logic, the first new method of dealing with uncertainty since the development of probability [Zadeh L.A., 1965].

5.2.1 Types of uncertainty

Uncertainty comes about when information is deficient, but information can be deficient in different ways. Uncertainty may be divided into several basic types [McNeill D. and Freiberger P., 1993; Klir G.J. and Yuan B., 1995; Klir G.J., 1989]:

- Fuzziness
- Ambiguity resulting from discord
- Ambiguity resulting from non-specificity

5.2.2 Fuzziness

Fuzziness is uncertainty resulting from vagueness. Most natural language descriptors are vague and somewhat uncertain, rather than precise. Following are a few examples of fuzzy, uncertain events in engineering within a ship:

i) Change lubricating oil within 100 days of operation.

ii) Filters should be cleaned when differential pressure is high.

iii) Maintain heavy fuel oil temperature above 90°C.

The vagueness in these operating instruction may lead the crew to use their own expert judgement to carry out the operation and hence there will be a non-uniform approach to maintenance and this could lead to failures within the operating system. From a safety assessment point of view, it would be difficult for the safety analyst to interpret these instructions and determine the interval of maintenance or the storage temperature of the heavy fuel oil.

5.2.3 Ambiguity resulting from discord

Discord can be defined as a conflict or dissonance. For example, in a probability distribution, *P(x)*, each probability measure is for a specific alternative in a set of exhaustive, mutually exclusive alternatives. Each *P(x)* expresses the "degree of belief" (based on some evidence) that a particular alternative is the correct alternative. Thus, the beliefs expressed in a probability distribution are in conflict with each other.

To illustrate this point, take the probability of failure of a component as an example. A 90% belief (probability) that the component will fail under certain conditions is in conflict with a 10% belief that the component will not fail. Probability theory can model only situations where there are no conflicting beliefs about mutually exclusive alternatives. If there are other aspects to the uncertainty (perhaps fuzziness), they are not captured in a probability theory model [Klir G.J., 1991].

5.2.4 Ambiguity resulting from non-specificity

Non-specificity is a lack of informativeness resulting from not clearly stating or distinguishing alternatives. Non-specificity is characterised by cardinalities (sizes) of relevant sets of alternatives. The more possible alternatives a situation has, the less specific the situation is (a situation is completely specific if there is only one possible alternative)[Klir G.J., 1991]. Because each probability in a probability distribution is completely specific to a particular alternative, probability theory is not capable of conceptualising non-specificity [Klir G.J., 1991]. Figure 5.1 shows the types of uncertainty along with a brief description of each uncertainty [Klir G.J. and Yuan B., 1995].

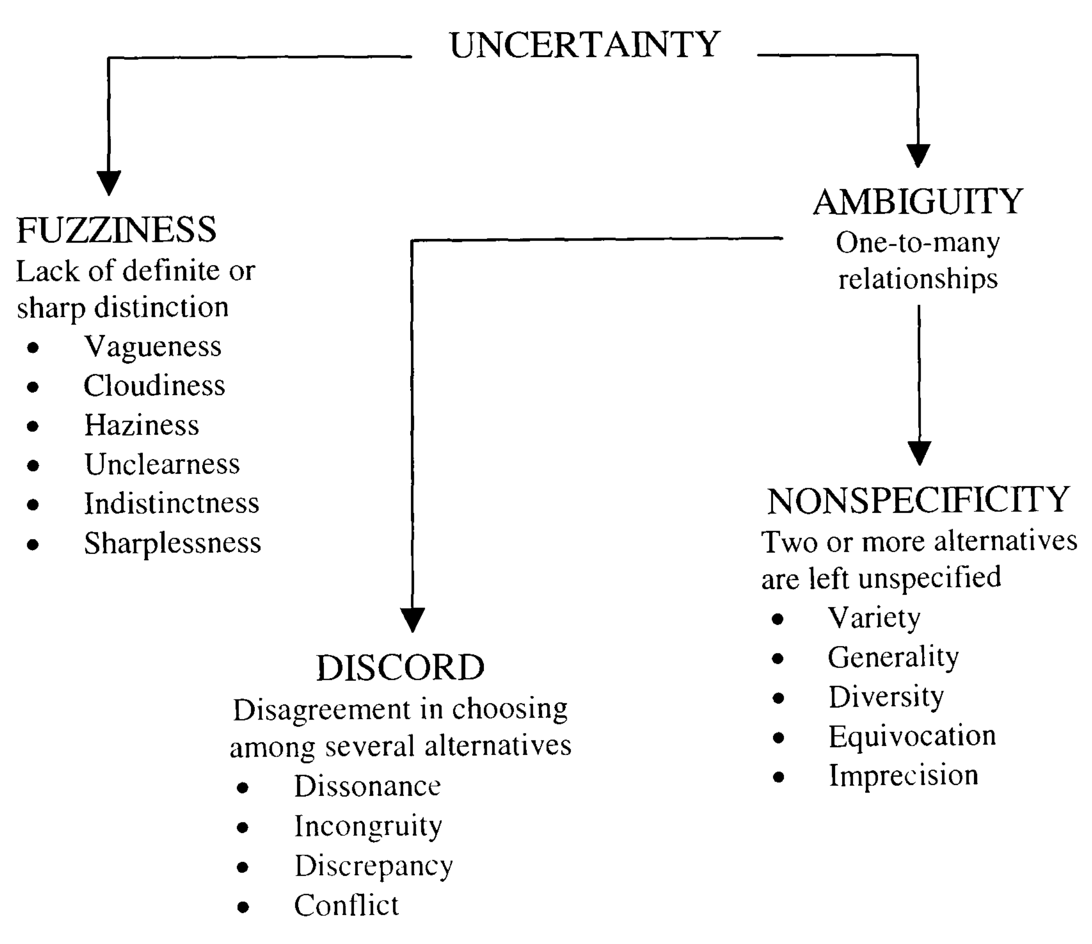


Figure 5.1 Types of uncertainty

Uncertainty in a safety analysis can be caused by three main factors as listed below [Villemeur A., 1992]:

i) *Uncertainties linked to the parameters* - for various reasons, the available information on dependability is uncertain: a small sample leading to a wide confidence interval, extrapolation of data from one installation to another, etc. Certain other parameters (delayed appearance of physical factors, time available after losing a system before undesirable effects ensue, etc.) connected with design or operation are also familiar but with elements of uncertainty. (Dependability is defined as the ability of an entity to perform one or several required functions under given conditions. This concept can encompass reliability, availability, maintainability, safety, durability, etc - or combinations of these abilities. Generally speaking, dependability is considered to be the science of failures and faults).

ii) *Uncertainties connected with modelling* - these are due to the use of an approximate dependability model. It is particularly true in the modelling of failures with a common cause, human error or software bugs. Generally, modelling can integrate all relevant variables without assessing their relationship in sufficient detail.

iii) *Uncertainties connected with the non-exhaustive nature of the analysis* - the analyst cannot be totally sure that his modelling has taken all important factors, relevant figures and significant interactions into account.

Analysing uncertainties therefore consists of identifying all the uncertainties and their repercussions on the assessment. Usually, only the first source of uncertainty is taken into account; an attempt is then made to assess the uncertainty of the final result (a measure of dependability) caused by the parameter uncertainty.

5.3 Fuzzy Set Theory Background

Fuzzy Set Theory (FST) was formalised by Prof. Lofti Zadeh at the University of California in 1965. The significance of fuzzy variables is that they facilitate gradual transition between states and consequently, possess a natural capability to express and deal with observation and measurement uncertainties.

Traditional variables, which may be referred to as *crisp variables* do not have this capability. Although the definition of states by crisp sets is mathematically correct, it is unrealistic in the face of unavoidable measurement errors. A measurement that falls into a close neighbourhood of each precisely defined border between states of a crisp variable is taken as evidential support for only one of the states, in spite of the inevitable uncertainty involved in decision. The uncertainty reaches its maximum at each border, where any measurement should be regarded as equal evidence for the two states on either side of the border. When dealing with crisp variables, the uncertainty is ignored; the measurement is regarded as evidence for one of the states, the one that includes the border point by virtue of an arbitrary mathematical definition. Bivalent set theory can be somewhat limiting if we wish to describe a 'humanistic' problem mathematically [Zadeh L.A., 1987]. For example, figure 5.2 illustrates bivalent sets to characterise the temperature of a room.

The limiting feature of bivalent sets is that they are mutually exclusive - it is not possible to have membership of more than one set. It is not accurate to define a transition from a quantity such as '*warm*' to '*hot*' by the application of one °C of heat. In the real world a smooth (unnoticeable) drift from '*warm*' to '*hot*' would occur. The natural phenomenon can be described more accurately by FST. Figure 5.3 shows how the same information can be quantified using fuzzy sets to describe this natural drift.

A set, A, with points or objects in some relevant universe, X, is defined as these elements of x that satisfy the membership property defined for A. In traditional 'crisp' sets theory each element of x either is or is not an element of A. Elements in a fuzzy set (denoted by ~, eg $\tilde{A}$) can have a continuum of degrees of membership ranging from complete membership to complete non-membership [Zadeh L.A., 1987].

The membership function $\mu(x)$, gives the degree of membership for each element $x \in X$. $\mu(x)$ is defined on [0,1] (The actual degree of membership of a system parameter in a particular group is indicated by the values between 0 and 1 inclusive). A membership of 0 means that the value does not belong to the set under consideration. A membership of 1 would mean full representation of the set under consideration. A membership

GRT	Gross Tonnage
HAZID	HAZard IDentification
HAZOP	HAZard and OPerability
HEI	Human Error Identification
HEP	Human Error Probability
HLA	Helicopter Landing Areas
HRA	Human Reliability Assessment
IEE	Institution of Electrical Engineers
ILO	International Labour Organisation
ILU	Institute of London Underwriters
IMO	International Maritime Organisation
IRPA	Individual Risk Per Annum
ITF	International Transport-workers Federation
LOA	Length Overall
MAIB	Marine Accident Investigation Branch
MAPPS	Maintenance Personnel Performance Simulation
MCA	Maritime Coastguard Agency
MIDS	Marine Incident Database System
MINMOD	Marine Investigation Module
MSC	Maritime Safety Committee
MTBF	Mean Time Between Failure
NCSR	National Centre for System Reliability
NPV	Net Present Value
ORCA	Operator Reliability Calculation and Assessment
OREDA	Offshore Reliability Data
OSHA	Operating and Support Hazard Analysis
P&I	Protection and Indemnity
PHA	Preliminary Hazard Analysis
PLL	Potential Loss of Life
PM	Preventive Maintenance
PMO	Preventive Maintenance Optimisation

somewhere between these two limits indicates the degree of membership. The manner in which values are assigned to a membership is not fixed and may be established according to the preference of the person conducting the investigation.

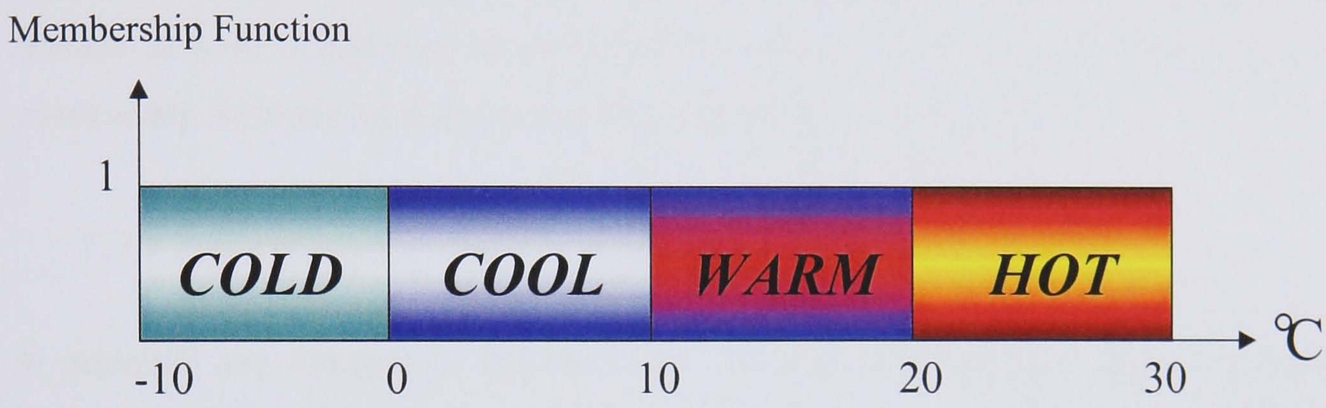


Figure 5.2 Bivalent set to characterise room temperature

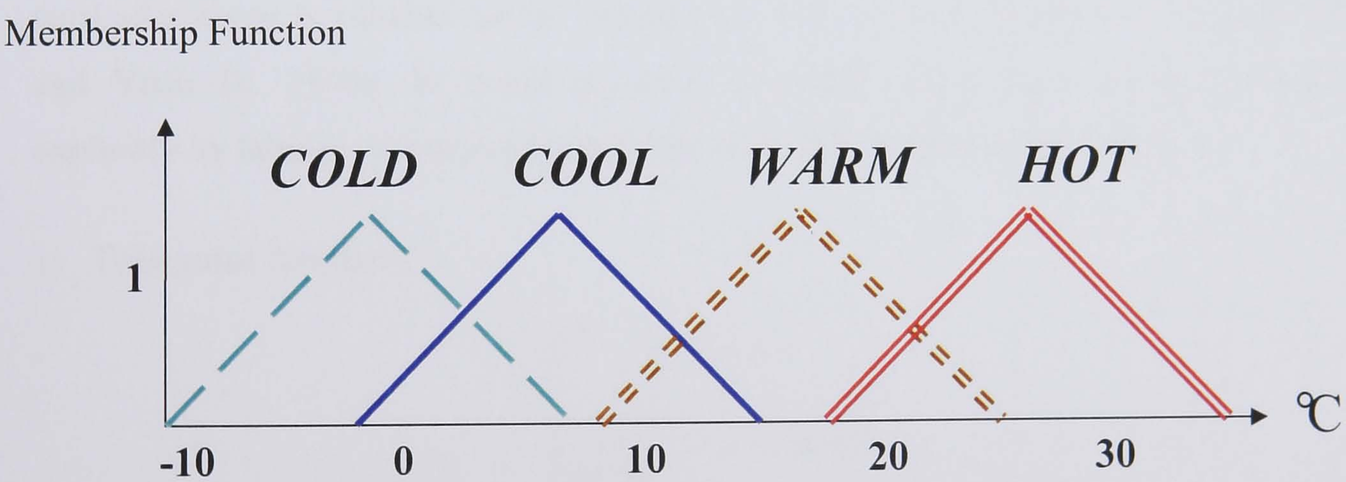


Figure 5.3 Fuzzy set to characterise room temperature

Formally $\tilde{A}$ is represented as the ordered pair $[x, \mu(x)]$:

$$\tilde{A} = \{(x, \mu(x)) | \, x \in X. \text{ and } 0 \leq \mu(x) \leq 1\} \qquad (1)$$

The use of a numerical scale for the degree of membership provides a convenient way to represent gradation in the degree of membership. Precise degrees of membership generally do not exist. Instead they tend to reflect sometimes subjective 'ordering' of the element in the universe.

Fuzzy sets can be represented by various shapes. They are commonly represented by S-curves, π-curves, triangular curves and linear curves. The shape of the fuzzy set depends on the best way to represent the data. In general the membership (often indicated on the vertical axis) starts at 0 (no membership) and continues to 1 (full membership). The domain of a set is indicated along the horizontal axis. The fuzzy set shape defines the relationship between the domain and the membership values of a set.

5.3.1 Types of membership functions

In principle any function of the form A: x → [0,1] describes a membership function associated with a fuzzy set Ã that depends not only on the concept to be represented, but also on the context in which it is used. The graphs of the functions may have very different shapes and may have some specific properties (e.g. continuity). Whether a particular shape is suitable can be determined only in the application context [Klir G.J. and Yuan B., 1995]. In many practical instances, fuzzy sets can be represented explicitly by families of parameterised functions, the most common being: -

1) Triangular functions

$$\tilde{A}(x) = \begin{cases} 0, \text{ if } x \leq a \\ \dfrac{x-a}{m-a}, \text{ if } x \in [a,m] \\ 1, \text{ if } x = m \\ \dfrac{b-x}{b-m}, \text{ if } x \in [m,b] \\ 0, \text{ if } x \geq b \end{cases}$$

where m is a modal value and a and b denote lower and upper bounds, respectively, for non-zero values of $\tilde{A}(x)$. Sometimes it is more convenient to use the notation explicitly highlighting the membership function parameters, in this case it is given by:

$$A(x;\, a,m,b) = max\{min[(x-a)/(m-a),(b-x)/(b-m)],0\} \quad (2)$$

2) Trapezoidal function.

$$\tilde{A}(x) = \begin{cases} 0, \text{ if } x < a \\ \dfrac{x-a}{m-a}, \text{ if } x \in [a,m] \\ 1, \text{ if } x \in [m,n] \\ \dfrac{b-x}{b-n}, \text{ if } x \in [n,b] \\ 0, \text{ if } x > b \end{cases}$$

Using equivalent notation, it is given by:

$$A(x;\, a,n,b) = max\{min[(x-a)/(m-a), 1, (b-x)/(b-n)], 0\} \qquad (3)$$

Figure 5.4 shows an example of a parameterised trapezoidal function. This is a graphical representation of the explicit families of parameterised functions defining the bounds of the function. In this example, the parameters *a, m, n* and *b* in equation (3) is given by -2.5, 0, 2.5 and 5, respectively.

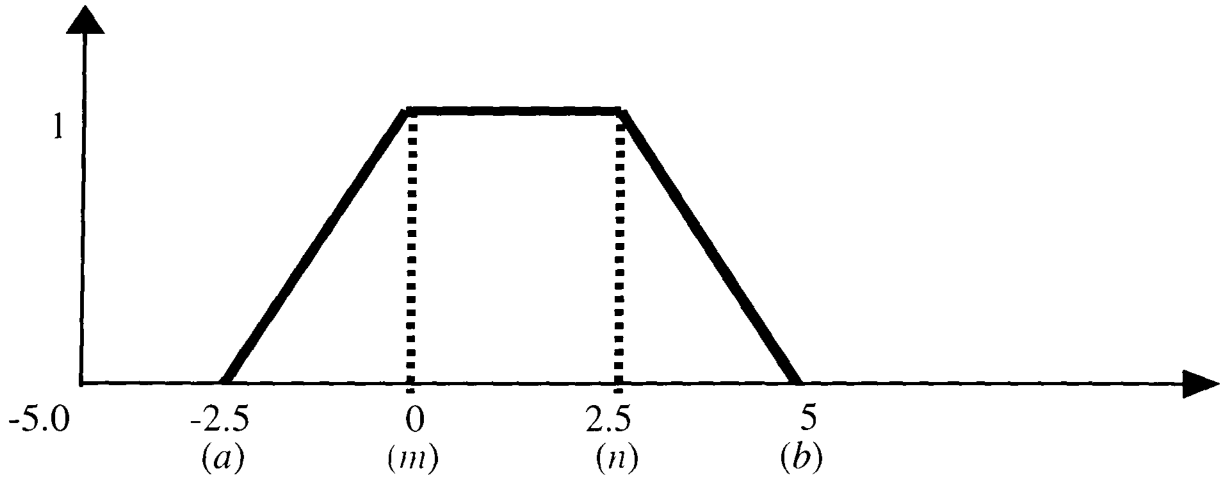


Figure 5.4 Parameterised trapezoidal function

Fuzzy sets can be characterised in more detail by referring to the features used in characterising the membership functions that describe them [Kandel A., 1986; Dubois D. et. al., 1993].

The "Support" of a fuzzy set A, denoted by $Supp(A)$, means that all elements of X belong to A to a non-zero degree [Kruse R. et al., 1994]. Formally, this is given by:

$$Supp(A) = \{ x \in X \mid A(x) > 0 \} \qquad (4)$$

Alternatively, the "Core" of a fuzzy set A is the set of all elements of X that exhibit a unit level of membership in A [Kruse R. et al., 1994], Formally, this is given by:

$$Core(A) = \{ x \in X \mid A(x) = 1 \} \qquad (5)$$

Figure 5.5 shows a graphical representation of the "Support" and "Core" of a fuzzy set. The "Support" and "Core" of fuzzy sets may be viewed as closely related concepts in the sense that they identify elements belonging to the fuzzy set and they are both sets. All elements of a "Core" are sub-named by the "Support". Interval $[a,d]$ is called the "Support" and interval $[b,c]$ is called the "Core".

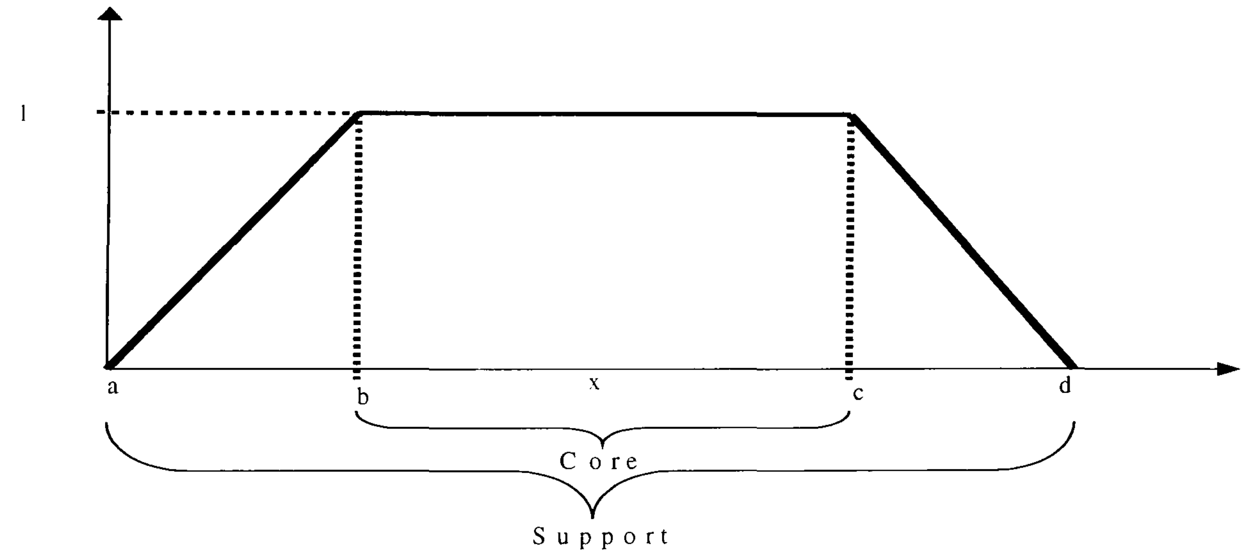


Figure 5.5 Representation of fuzzy set "Support" and "Core"

5.3.2 Representation theorem

Any fuzzy set can be regarded as a family of fuzzy sets. This is the essence of an identity principle known also as the representation theorem. To explain this construction, it is required to define the notion of an α –cut of a fuzzy set. The α –cut of

A, denoted by A_α, is a set consisting of those elements in the universe X whose membership values exceed the threshold level α. This is formally represented by:

$$A_\alpha = \{ x | A(x) \geq \alpha \} \qquad (6)$$

In other words, A_α consists of elements of x identified with A to a degree of at least α. In particular, the highest level, $\alpha = 1$, determines a set of x totally belonging to A. Clearly the lower the level of α, the more elements are admitted to the corresponding α-cut, that is, if $\alpha_1 > \alpha_2$ then $A_{\alpha 1} \subset A_{\alpha 2}$. The representation theorem states that any fuzzy set A can be decomposed into a series of its α-cuts. This can be represented by:

$$A = \bigcup_{\alpha \in (0,1)} (\alpha A_\alpha), \text{ or equivalently}$$

$$A(x) = \underset{\alpha \in [0,1]}{Sup} [\alpha A_\alpha (x)] \qquad (7)$$

Conversely, any fuzzy set can be "reconstructed" from a family of nested sets (assuming that they satisfy the constraint of consistency: if $\alpha_1 > \alpha_2$ then $A_{\alpha 1} \subset A_{\alpha 2}$. This theorems' importance lies in its underscoring of the very nature of the generalisation provided by fuzzy sets. Furthermore, the theorem implies that problems formulated in the framework of fuzzy sets (such as risk and reliability analysis) can be solved by transforming these fuzzy sets into their corresponding families of nested α-cuts and determining solutions to each using standard, non-fuzzy techniques. Subsequently, all the partial results derived in this way can be merged, reconstructing a solution to the problem in its original formulation based on fuzzy sets. By increasing the number of quantisation levels of the membership values (that is the α-cuts), the reconstruction can be made more detailed. Figure 5.6 shows a diagrammatic representation of α-cuts. Clearly, the lower the level of α, the more elements are admitted to the corresponding α-cut, that is, if $\alpha_1 > \alpha_2$ then $A_{\alpha 1} \subset A_{\alpha 2}$

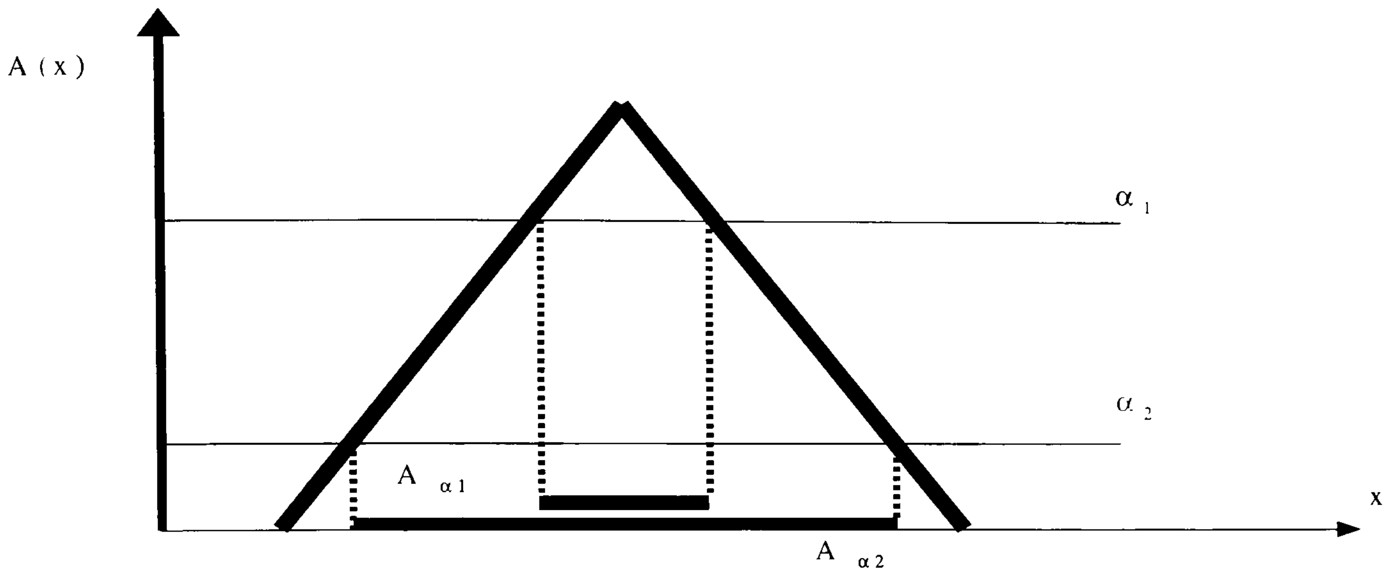


Figure 5.6 Representation of α-cuts on a fuzzy set

5.3.3 Application of FST

Since FST was proposed almost four decades ago, it has found many useful applications. The linguistic approach based on fuzzy sets has given very good results for modelling qualitative information. It has been widely used in different fields, for example, information retrieval [Bordogna G. and Pasi G., 1993], clinical diagnosis [Degani R. and Bortolan G., 1988], marketing [Yager R.R. et. al., 1994], risk in software development [Lee H.M., 1996a; Lee H.M., 1996b], technology transfer strategy selection [Chang P. and Chen Y., 1994], education [Law C.K., 1996], decision making [Bordogna G. et. al., 1997], environmental engineering [Deshpande A.W., 1999], and many more. A review by Maiers and Sherif in 1985, covered over 450 papers addressing FST application in areas of automation control, decision making, biology and medicine, economics and the environment [Maiers J. and Sherif Y.S., 1985].

The use of FST in system safety and reliability analyses could prove to be a useful tool, as these analyses often require the use of subjective judgement and uncertain data. By allowing imprecision and approximate analysis, FST helps to restore integrity to reliability analyses by allowing uncertainty and not forcing precision where it is not possible. However, the theory can be difficult to use directly. The use of linguistic variables allows a flexible modelling of imprecise data and information. A linguistic variable differs from a numerical variable in that its values are not numbers but words or sentences in a natural or artificial language. Since words in general are less precise than numbers, the concept of a linguistic variable serves the purpose of providing a means of approximate characterisation of phenomena, which are too complex or ill defined to be amenable to description in conventional quantitative terms [Schmucker K.J., 1984]. More specifically, the fuzzy sets, which represent the restriction associated with the values of a linguistic variable, may be viewed as summaries of various sub-classes of elements in a universe of discourse (a universe of discourse is the range of all possible values for an input to a fuzzy system). This is analogous to the role played by words and sentences in a natural language.

5.4 A Proposed Approach

The proposed approach is divided into two main modelling categories, that is, likelihood probability (Part 1) and severity of consequences (Part 2). It involves several steps, which are represented in the flowchart shown in figure 5.7. A combination of FST and expert judgement is used to accomplish the modelling of the two parameters. The outcome of which is used to rank the risk associated with an event failure according to its priority. Part 1 of the approach uses Fault Tree Analysis (FTA) to identify the critical components of a system [Pillay A. et. al., 2000]. Using this FTA, fuzzy arithmetic calculation is performed on the basic events to obtain the fuzzy probability estimates of the primary events. The results are left in the linguistic state to enable integration with the analysis of severity of consequences.

In Part 2 of the approach, the severity of a failure is assessed for its effect on four categories, as will be discussed later. The results of the analysis in Parts 1 and 2 are combined using the min-max inference rule to obtain a linguistic term for the risk. This linguistic term is then defuzzified using the weighted mean of maximum method to produce the risk ranking.

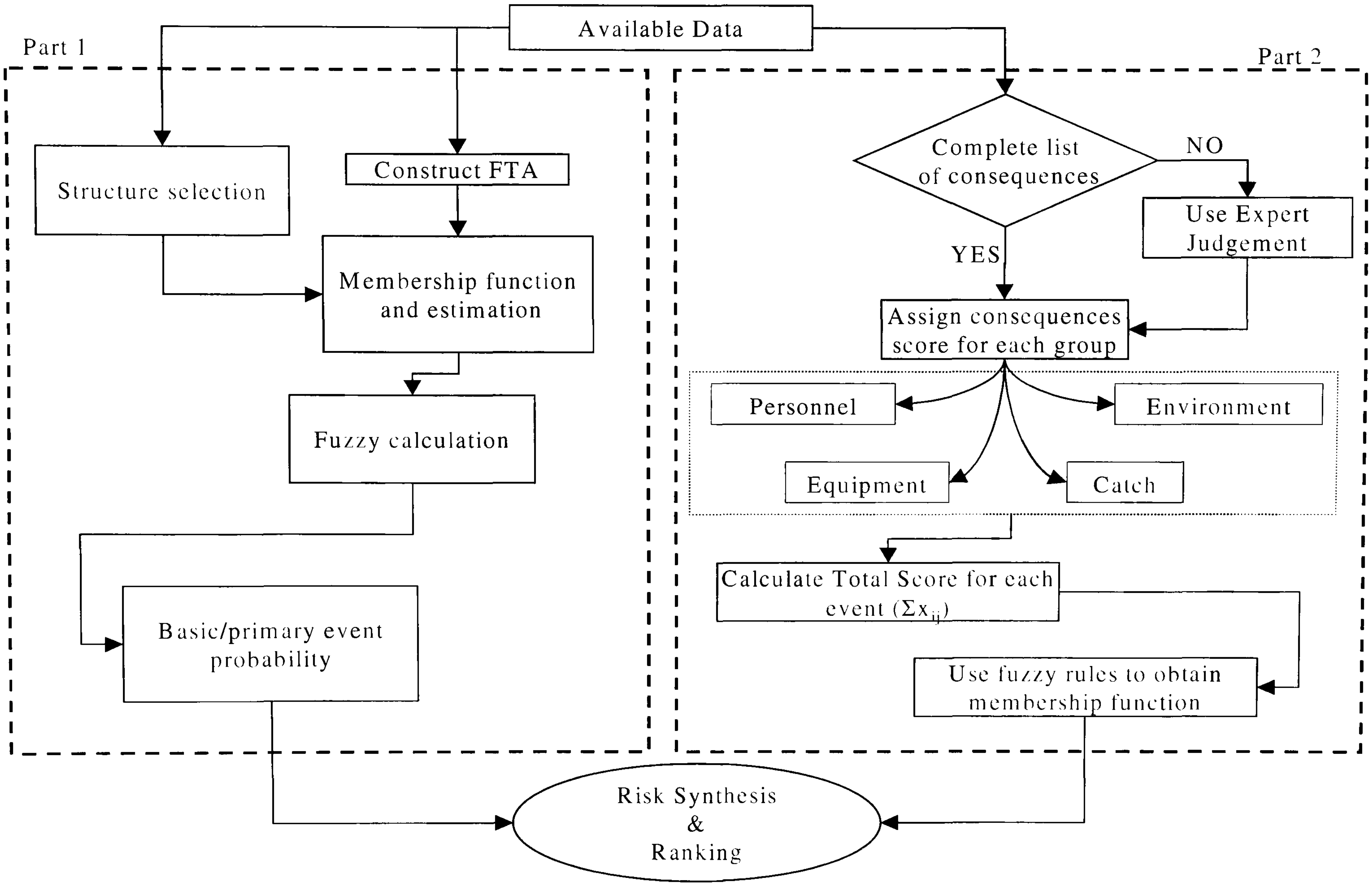


Figure 5.7 Flowchart of the proposed approach

PAGE NUMBERING AS ORIGINAL

The first step of the proposed approach is to establish the type of data that is available for analysis. Depending on the size and organisational structure of the company, this data will vary in terms of its format and availability. The data available from fishing vessels are most likely repair data that would just reflect the date the repair was carried out and the spares consumed. Such data should be restructured to enable analysis using the fuzzy set approach.

The consequences of an event may not be documented in a format where it is readily useable for analysis. The severity of the consequence could be determined by the cost incurred from the result of the failure. This however may only be limited to equipment loss, production loss, environmental clean up cost, etc. The injury or loss of life (due to the failure of an equipment) is normally expressed in terms of number of casualties and the extent of the injury (bruises, required shore medical assistance, permanent disablement or death).

5.4.1 Part 1: Probability of failure event occurrence

Constructing fault tree - Once the failure data has been gathered, it is grouped and sorted by its equipment/sub-system and finally the system to which the component belongs. The top event of the fault tree will be the failure of the equipment (e.g. main winch failure) while the initiating events and basic events will be the component failure (e.g. seal leakage, brake failure, control valve failure, etc). A full description of FTA has been provided in chapter 3 (section 3.8). It is best to construct a fault tree for equipment within a system separately as it enables data handling and analysis to be conducted. The individual fault trees can later be collated to analyse the system failure. Fault tree construction can be achieved with the use of computer software packages such as Fault Tree +V6.0 and AvSim+ [Fault Tree +, 1995; AvSim+, 1998].

Structure selection - In the structure selection phase, the linguistic variable is determined with respect to the aim of the modelling exercise. Informally, a linguistic variable is a variable whose values are words or sentences rather than numbers. Considering the available data at hand and the aim of this approach, the linguistic variable is determined to be the likelihood of occurrence of an undesired critical event

PMS	Preventive Maintenance Schedule
PSF	Performance-Shaping Factor
QRA	Quantitative Risk Analysis
RAM	Reliability, Availability and Maintainability
RCM	Reliability Centred Maintenance
RCML	Risk Control Measure Log
RCO	Risk Control Option
RCOL	Risk Control Option Log
RCT	Risk Contribution Tree
RNLI	Royal National Lifeboat Institution
RPN	Risk Priority Number
RRN	Risk Ranking Number
SART	Search And Rescue Transponder
SFE	System Failure Analysis
SHA	System Hazard Analysis
SLIM-MAUD	Success Likelihood Index Method-Multi-Attribute Utility Decomposition
SNAMES	Society of Naval Architects and Marine Engineers
SRM	Sandia Recovery Model
SSHA	Subsystem Hazard Analysis
STCW	Standard of Training, Certification and Watch keeping
THERP	Technique of Human Error Rate Prediction
UKEAE	United Kingdom Atomic Energy Authority
USCG	United States Coast Guard

that is, the probability of failure occurring. The linguistic terms to describe this variable are then decided, for example, Very High, High, Moderate, Low and Remote.

Membership function and estimation - Six classes of experimental methods help to determine membership function: horizontal approach, vertical approach, pairwise comparison, inference based on problem specification, parametric estimation and fuzzy clustering [Pedrycz W. and Gomide F., 1998]. The method selected depends heavily on the specifics of an application, in particular, the way the uncertainty is manifested and captured during the sampling of data. The membership function chosen must be able to represent the available data in the most suitable and accurate manner. Due to the nature of the arithmetic involved, the shape of the membership function suited for the proposed approach would either be triangular or trapezoidal, therefore the horizontal or vertical approach for function determination is applied [Pedrycz W. and Gomide F., 1998]. The vertical method takes advantage of the identity principle and 'reconstructs' a fuzzy set via identifying its α-cuts. After several levels of α are selected, the investigator is required to identify the corresponding subset of X whose elements belong to A to a degree not less than α. The fuzzy set is built by stacking up the successive α-cuts. Figure 5.8 shows an example of the stacking process of α-cuts.

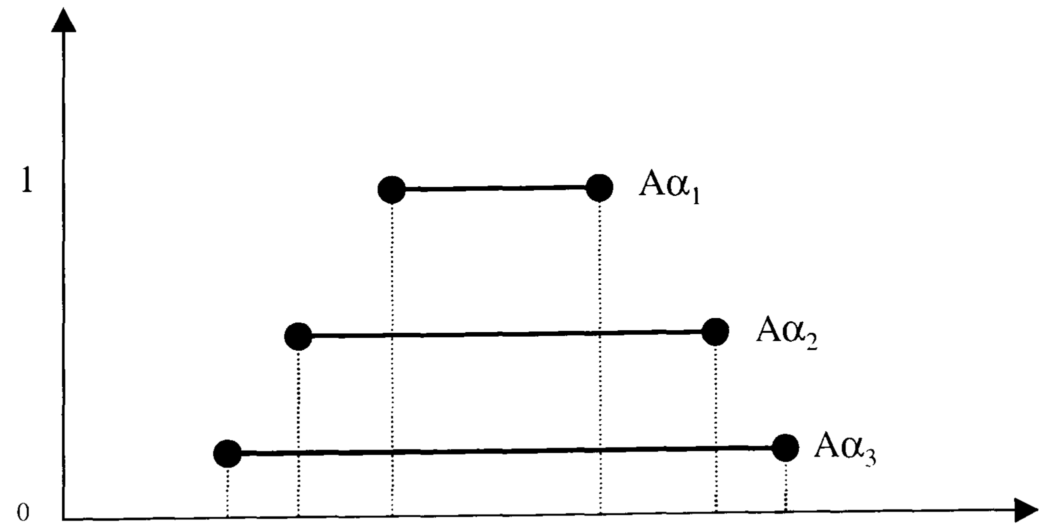


Figure 5.8 Vertical approach for function determination

Fuzzy calculation in fault trees - Given the critical event or undesired condition (top event), a fault tree can be developed using backward logic to create a network of intermediate events linked by logic operators (usually AND and OR operators) down to the initiating basic events. The fault tree itself is the logic structure relating the top event to the primary events. These primary/basic events may be related to human error (operators, design or maintenance), hardware or software failures, environmental conditions or operational conditions.

The probability of an event defined as a fuzzy set is developed as below [Bowles J.B. and Paláez C.E.,1995]. Let S be a sample space and P a probability measure defined on S. Then,

$$P(S) = \int_S dP = 1$$

If $E \subseteq S$ is an event then

$$P(E) = \int_S C_E(x)dP$$

Where $C_E(x) =$ 1 if $x \in E$

0 otherwise

Zadeh has observed that $P(E)$ can be viewed as the expected value of the characteristic function that defines the set E [Zadeh L.A., 1987]. By analogy, he defines the probability of the fuzzy set $\tilde{A}$ as the expected value of the membership function for $\tilde{A}$:

$$\mathbf{P}(\tilde{A}) = \int_S \mu_{\tilde{A}}(x)dP \qquad (8)$$

On a discrete sample space, $S = \{x_1, x_2, x_3 \ldots\ldots x_n\}$, this is,

$$\mathbf{P}(\tilde{A}) = \sum_{i=1}^{n} \mu_{\tilde{A}}(x_i)P(x_i) \qquad (9)$$

Intuitively, equation (8) and (9) define the probability of a fuzzy event as the summation over all elements, of the probability the event occurs weighted by the degree to which the element is a member of the event. Alternatively, it can be viewed as the probability of the possibility of the fuzzy event.

The following properties of the probability of ordinary events also hold for the probabilities of fuzzy events [Terano T. et. al., 1992].

- $P(\tilde{A}) \leq P(\tilde{B})$ if $\tilde{A} \subseteq \tilde{B}$
- $P(\overline{\tilde{A}}) = 1 - P(\tilde{A})$
- $P(\tilde{A} \cup \tilde{B}) = P(\tilde{A}) + P(\tilde{B}) - P(\tilde{A} \cap \tilde{B})$

For most system and components, the organisational structure can be described as either 'parallel' or 'series' or a combination of series and parallel as seen in figures 5.9, 5.10 and 5.11

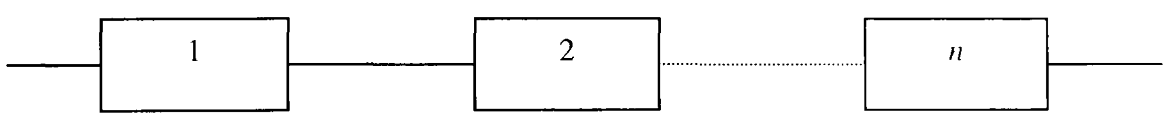


Figure 5.9 Series System

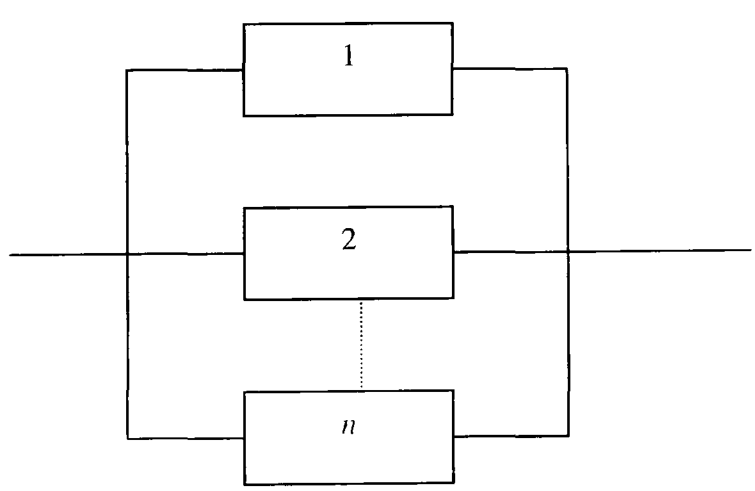


Figure 5.10 Parallel System

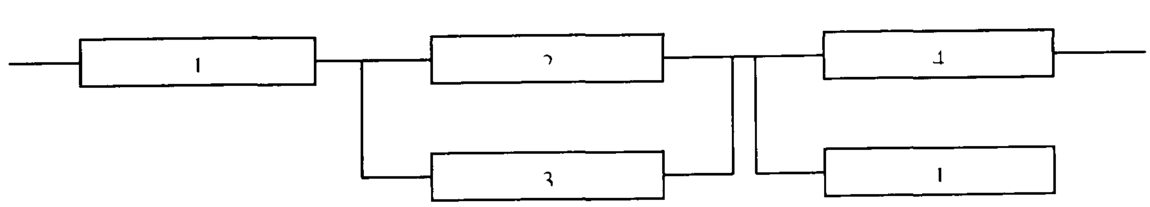


Figure 5.11 Series-Parallel System

System reliability can be analysed probabilistically as shown below:

Let P_i = probability of failure of component *i*. Then

R_i = reliability of component = 1 - P_i

Let P_{sys} = system probability of failure. Then

R_{sys} = system reliability = 1 – P_{sys}

For a parallel system, the system will work as long as at least one component is in operational order. If, as is traditionally assumed, components are independent and the system is either working or failed, the system probability failure (P_{sys}) is the product of the individual component failure probabilities:

$$P_{sys} = P_1 \bullet P_2 \bullet P_3 \bullet \ldots\ldots P_n. \qquad (10)$$

Applying equation (10) to a two component (A and B) parallel system with fuzzy probabilities will give:

$$\tilde{P}_{sys} = \tilde{P}_A \tilde{P}_B \qquad (11)$$

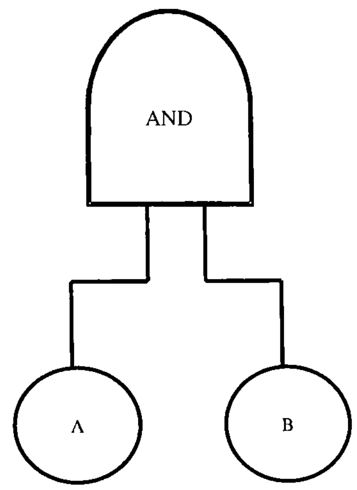
In a series system, all constituent components must be operational for the system to work. Series systems are analysed in terms of their component reliabilities: $R_{sys} = R_1 \bullet R_2 \bullet R_3 \bullet R_n$. The analysis of a series system using reliabilities is identical to that of a parallel system using failure probabilities. In terms of failure probabilities for the series system:

$$P_{sys} = 1 - [(1 - P_1)(1 - P_2)(1 - P_3)\ldots\ldots (1 - P_n)] \qquad (12)$$

Applying equation (12) to a two component (A and B) series system with fuzzy probabilities will give:

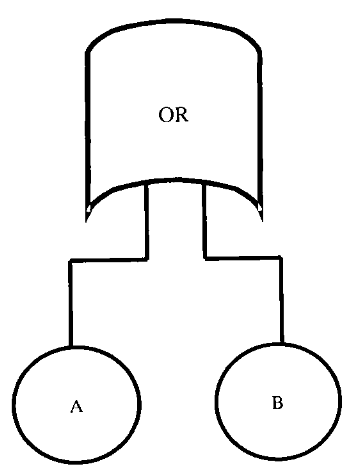
$$\tilde{P}_{sys} = [1 - (1 - \tilde{P}_A)(1 - \tilde{P}_B)] \qquad (13)$$

When two basic events represent the input to an AND gate as shown in figure 5.12, it can be assumed that these two events are in a parallel configuration. It denotes that the occurrence of both events will cause the AND gate to be operative and the probability will be given by equation (11). For an OR gate with two basic events as its input as shown in figure 5.13, it can be considered that the two events are in a series configuration. This denotes that if either events occur, the OR gate will be operative and the probability will be given by equation (13) [Bowles J.B. and Paláez C.E., 1995].



$$\tilde{P}_{sys} = \tilde{P}_A \tilde{P}_B$$

Figure 5.12 AND gate



$$\tilde{P}_{sys} = [1-(1-\tilde{P}_A)(1-\tilde{P}_B)]$$

Figure 5.13 OR gate

Fuzzy arithmetic operations - In standard fuzzy arithmetic, basic operations on real numbers are extended to those on fuzzy intervals. A fuzzy interval A is a normal fuzzy set on R (set of real numbers) whose α-cuts for all $\alpha \in (0,1]$ are closed intervals of real numbers and whose support is bounded by A.

Two common ways of defining the extended operation are based on the α-cut representation of fuzzy intervals and on the extension principle of FST [Kaufman A. and Gupta M.M., 1985; Klir G.J. and Yuan B., 1995]. When α-cut representation is employed, arithmetic operations on fuzzy intervals are defined in terms of arithmetic operations on closed intervals. To define the individual arithmetic operation specifically, let the symbols $[a_1^\alpha, a_2^\alpha]$ and $[b_1^\alpha, b_2^\alpha]$ denote for each $\alpha \in (0,1]$ the α-cuts of fuzzy intervals A and B, respectively. Using this notation, the individual arithmetic operations on the α-cuts of A and B are defined by the well known formulas from interval analysis [Kaufman A. and Gupta M.M., 1985; Klir G.J. and Yuan B., 1995] given below:

$$A_\alpha + B_\alpha = [a_1^\alpha + b_1^\alpha, a_2^\alpha + b_2^\alpha] \qquad (14)$$

$$A_\alpha - B_\alpha = [a_1^\alpha - b_2^\alpha, a_2^\alpha - b_1^\alpha] \qquad (15)$$

$$A_\alpha \text{ x } B_\alpha = [a_1^\alpha b_1^\alpha, a_2^\alpha b_2^\alpha] \qquad (16)$$

$$A_\alpha / B_\alpha = [a_1^\alpha / b_2^\alpha, a_2^\alpha / b_1^\alpha] \qquad (17)$$

$$A_\alpha \pm k = [a_1^\alpha, a_2^\alpha] \pm k = [a_1^\alpha \pm k, a_2^\alpha \pm k] \qquad (18)$$

$$A_\alpha \text{ x } k = [a_1^\alpha, a_2^\alpha] \text{ x } k = [ka_1^\alpha, ka_2^\alpha] \qquad (19)$$

Equations (16) and (17) are true for all non-negative numbers. Figures 5.14 and 5.15 illustrate simple addition and subtraction operations of α-cuts of sets A and B respectively.

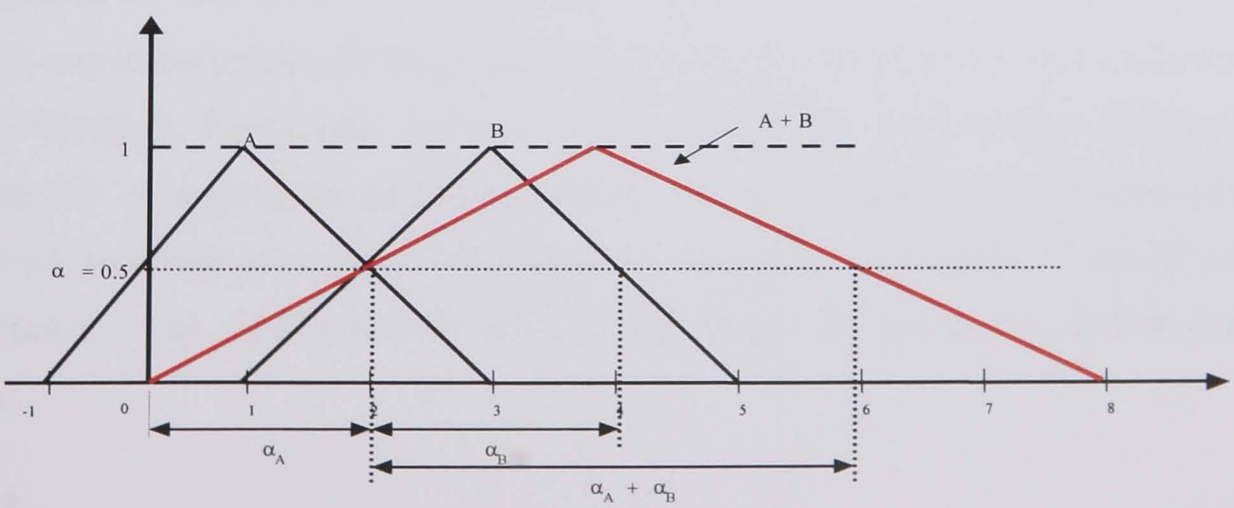


Figure 5.14 Addition operation on α-cut

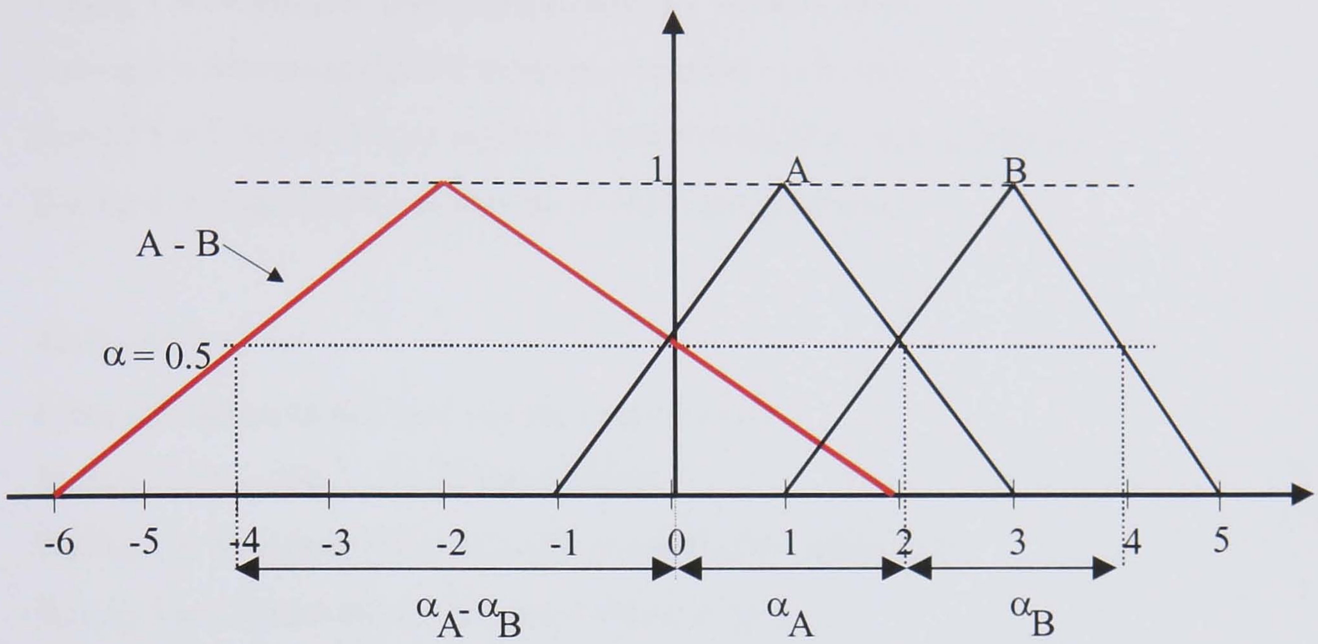


Figure 5.15 Subtraction operation on α-cut

5.4.2 Part 2: Severity of consequences

List of consequences - When carrying out a comprehensive analysis, it is important that all the consequences of a failure is considered. It has been noted that due to the poor documentation of accidents on fishing vessels, the list of identifiable consequences are limited to the serious or life threatening ones, for example, death of a crew, complete loss of a vessel/equipment and so on. Therefore, expert judgement should be used to compile a list of consequences and complement the historical data. This can be achieved in the form of a FMEA [Smith D.J., 1992]. Upon being satisfied that all the consequences for each event/failure have been compiled, the analyst has to assign them into their respective groups. In the proposed approach, four groups have been identified, that is, Personnel, Equipment, Environment and Catch. For each event or failure, a rating from 1 - 4 is given for each of the groups. The ratings describe the consequences of an event occurring in linguistic terms such as 'Negligible', 'Marginal', 'Critical' and 'Catastrophic'. The significance of each of the ratings are listed and described as follows:

Personnel:

Effect of failure of the item on personnel (worst case always assumed).

Rating 1 = Negligible (No or little damage- bruises/cuts)

Rating 2 = Marginal (Minor injuries - treatable on board)

Rating 3 = Critical (Major injuries – requires professional attention)

Rating 4 = Catastrophic (Death/permanent disablement)

Environment:

Effect of failure of the item on the environment

Rating 1 = No effect (No or little effect)

Rating 2 = Marginal effect (Can be controlled by ship-staff)

Rating 3 = Critical effect (Requires shore assistance)

Rating 4 = Catastrophic effect (permanent damage to the environment)

Equipment:

Effect of failure on machinery or system in terms of down time if failure occurs and cost of repair.

Rating 1 = Negligible (No or little attention needed - cleaning up/drying)

Rating 2 = Marginal (Minor repair – few hrs lost)

Rating 3 = Critical (Major repair – few days lost)

Rating 4 = Catastrophic (Destruction of equipment - Total plant shutdown)

Catch:

Effect of failure on fishing operation in terms of catch effected: -

Rating 1 = No effect (No or little effect)

Rating 2 = Marginal effect (Catch affected for a few hours)

Rating 3 = Critical effect (Catch affected for a few days)

Rating 4 = Catastrophic effect (No catch for a few months)

Calculate Total Score (Σx_{ij}) - Upon assigning a score for each group, a table is generated as shown in table 5.1. From this table, a "Total Score" is calculated by summing the score of each individual group for an event. This total score will later be used to assign the membership function for that event using fuzzy rules.

	Personnel	Environment	Equipment	Catch	Total Score(ΣX_{i1})
Failure Y_1	X_{11}	X_{21}	X_{31}	X_{41}	ΣX_{i1}
Failure Y_2	X_{12}	X_{22}	X_{32}	X_{42}	ΣX_{i2}
Failure Y_3	X_{13}	X_{23}	X_{33}	X_{43}	ΣX_{i3}

Table 5.1 Event score

Fuzzy rules - The fuzzy rules determining the membership function of each event are divided into 4 categories i.e. Hazard Class 1(HC_1), HC_2, HC_3 and HC_4. The maximum score of an event is used to assign that particular event to the appropriate hazard class. Therefore, if an event has a score of [2,2,1,1] for each group respectively, it would be assigned to HC_2 (the maximum score for that event is 2 for the Personnel and Environment categories).

Fuzzy rules are generated based on available historical data, experience and complemented by expert knowledge. Where possible, logbooks are analysed for casualty and accident reports to develop the following rules:

Hazard Class 1 (HC_1)

If an event has a score of [1,1,1,1], which entails that for all categories considered, the effect of the failure is negligible, then the total effect of that failure on the system and environment should be negligible as well. Hence,

1) If $\Sigma X_{ij} = 4$, then Negligible................(1.0)

Hazard Class 2 (HC_2)

The minimum score possible in the HC_2 category is 5, i.e. [2,1,1,1] or any variation of this score. The maximum possible score is 8, i.e. [2,2,2,2], therefore the range of membership function between these two extremities is assigned so as to ensure a smooth transition between limits to have overlapping of functions. Hence: -

2) If $X_{ij\,max} = 2$, and $\Sigma X_{ij} = 5$ then 0.8 Negligible, 0.6 Marginal.........(2.0)

$\Sigma X_{ij} = 6$ then Marginal, 0.2 Critical..................(2.1)

$\Sigma X_{ij} = 7$ then 0.5 Marginal, 0.8 Critical.............(2.2)

$\Sigma X_{ij} = 8$ then Critical, 0.2 Catastrophic.............(2.3)

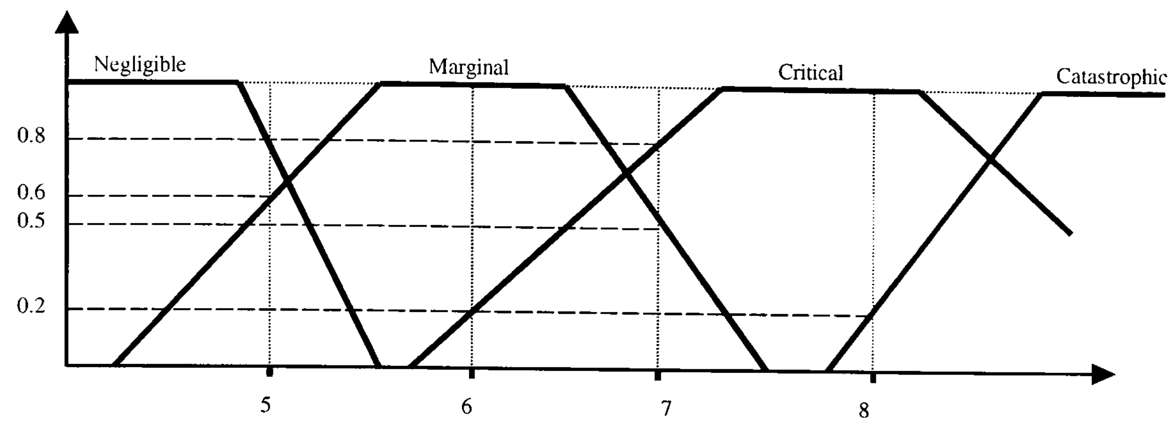


Figure 5.16 Hazard class 2

Hazard Class 3 (HC_3)

The minimum score possible in the HC_3 category is 6, i.e. [3,1,1,1] or any variation of this score. The maximum possible score is 12, i.e. [3,3,3,3]. When assigning the linguistic membership function for HC_3, it is important to compare the values with that of the HC_2 to ensure that it does not contradict the rules generated for that hazard class. For the same total score in HC_2 and HC_3, the linguistic membership function for HC_3 (for that particular score) should logically reflect a more severe consequence. For example, for a total score of 7 for HC_2 and HC_3, which would have a combination of [2,2,2,1] and [3,2,1,1] respectively, using expert judgement, one would say that although both classes have the same total score, a total score of 7 for HC_3 would entail a more severe consequence. Hence the membership function for HC_3 and a total score of 7 would be 0.8 Critical, 0.2 Catastrophic which is higher than the membership function for HC_2 with the same total score of 7, which is 0.5 Marginal, 0.8 Critical. Using this method, the rules for HC_3 are generated for the other values of its total scores and are reflected below:

3) If $X_{ij\,max} = 3$, and $\Sigma X_{ij} = 6$ then 0.5 Marginal, Critical............................(3.0)

$\Sigma X_{ij} = 7$ then 0.8 Critical, 0.2 Catastrophic..................(3.1)

$\Sigma X_{ij} = 8$ then 0.5 Critical, 0.5 Catastrophic..................(3.2)

$\Sigma X_{ij} = 9$ then 0.2 Critical, 0.8 Catastrophic..................(3.3)

$\Sigma X_{ij} = 10$ then Catastrophic....................................(3.4)

$\Sigma X_{ij} = 11$ then Catastrophic....................................(3.5)

$\Sigma X_{ij} = 12$ then Catastrophic....................................(3.6)

List of Figures

The above rules can be represented graphically as seen in figure 5.17.

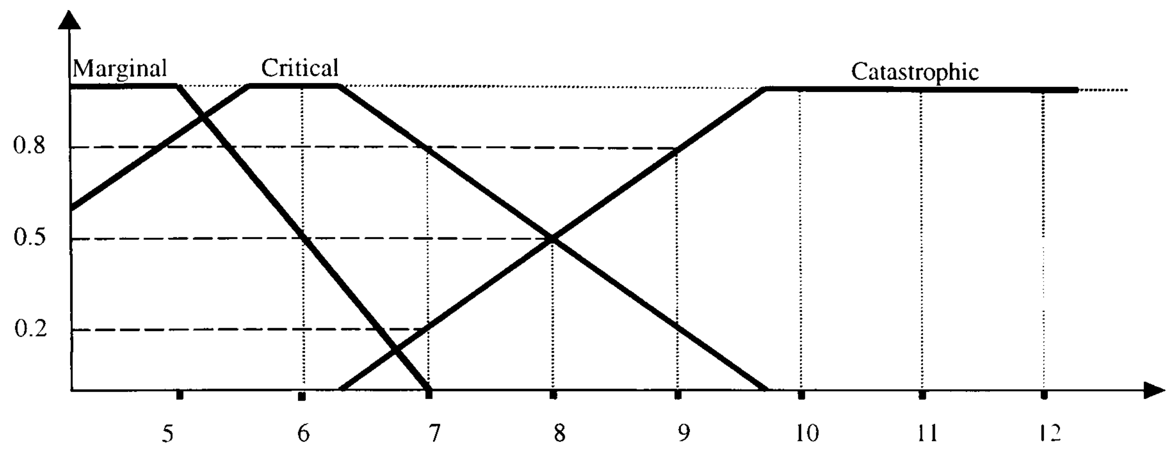


Figure 5.17 Hazard class 3

Hazard Class 4 (HC_4)

4) If $X_{ij\ max} = 4$, and $\Sigma X_{ij} \geq 7$ then Catastrophic....................................(4.0)

It is necessary to assign a hazard class for each event as the consequences of the event are considered for different groups. Grouping each event into a hazard class allows direct comparison with other events and enables the effects of a failure to be compared based on its linguistic terms assigned to it. For example, if an event A has a score of [3,3,1,1] and a total of 8 and event B has a score of [2,2,2,2] which also gives a total of 8, from experience and expert judgements, it can be said that event A is more serious in nature. Hence, it should be assigned a linguistic term which must be 'more severe' compared to event B. To enable this distinction between events, which have the same total score, hazard classification is introduced, i.e. HC_1, HC_2, etc. Therefore, the membership function for event A and B will be obtained from Rules No.(3.2) and (2.3) respectively. At this stage of the proposed approach, each event would be assigned likelihood and consequences of occurrence. The next step would be to analyse these two parameters and provide a risk ranking number for each event.

5.4.3 Risk assessment

The risk associated with a failure increases as either the severity of the consequences of the failure or the failure probability increases. The severity of an event is ranked according to the seriousness of the effect of the failure. Judgement of the severity of a failure consequence is, by its very nature, highly subjective. Using a priority matrix, the "riskiness" of a failure can be obtained. The risk posed by the failure is expressed in linguistic terms such as *'Very Important'*, *'Important'*, *'Moderate'* and *'Low'*. This matrix is based on the probability of occurrence and the severity of the consequence. Table 5.2 displays the various combinations of these two parameters.

The interpretation of hazard risk ranking is given as below:

- Very Important ⇒ Needs immediate corrective action.
- Important ⇒ Review and corrective action to be carried out.
- Moderate ⇒ Review to be carried out and corrective action implemented if found to be cost effective.
- Low ⇒ Review subject to availability of revenue and time.

		Severity of Occurrence			
		NEG	*MARG*	*CRIT*	*CAT*
Probability of Occurrence	***REMOTE***	**RN**	**RM**	**RC**	**RCAT**
	LOW	**LN**	**LM**	**LC**	**LCAT**
	MODERATE	**MN**	**MM**	**MC**	**MCAT**
	HIGH	**HN**	**HM**	**HC**	**HCAT**
	VERY HIGH	**VHN**	**VHM**	**VHC**	**VHCAT**

Very important | Important

Moderate | Low

Table 5.2 Probability and consequence matrix

From this table, a risk ranking in linguistic terms can be obtained for the failure of a system/sub-system or component. For example, if the probability of failure is *'High'* and the severity is *'Marginal'*, then the risk would be classified as *'Important'*. In order to utilise this information for the decision making process, a crisp number has to be obtained from the linguistic terms to rank the risk according to its priority. One common procedure for ranking risk is to use the RPN or 'Risk Priority Number'. This method provides a numerical ranking for each term and multiplies them to assess the riskiness [Loughran C.G. et. al., 1999].

Fuzzy set approach provides a more flexible and meaningful way of assessing risk. The analysis uses linguistic variables to describe severity and probability of occurrence of the failure. These parameters are 'fuzzified' to determine their degree of membership in each input class using the membership functions developed. The resulting fuzzy inputs are evaluated using the linguistic rule base to yield a classification of the 'riskiness' of the failure and an associated degree of membership in each class. This fuzzy conclusion is then defuzzified to give a single crisp priority for the failure.

Figure 5.18 shows the membership function of the riskiness of an event on an arbitrary scale, which would later be used to defuzzify the fuzzy conclusion and rank the risk according to a priority number. The membership function used is a triangular function which can be developed using the horizontal or vertical approach based on expert judgement [Pedrycz W. and Gomide F., 1998]. Unlike the trapezoidal function, the membership value of 1 in the triangular function is limited to only one value of the variable on the x-axis.

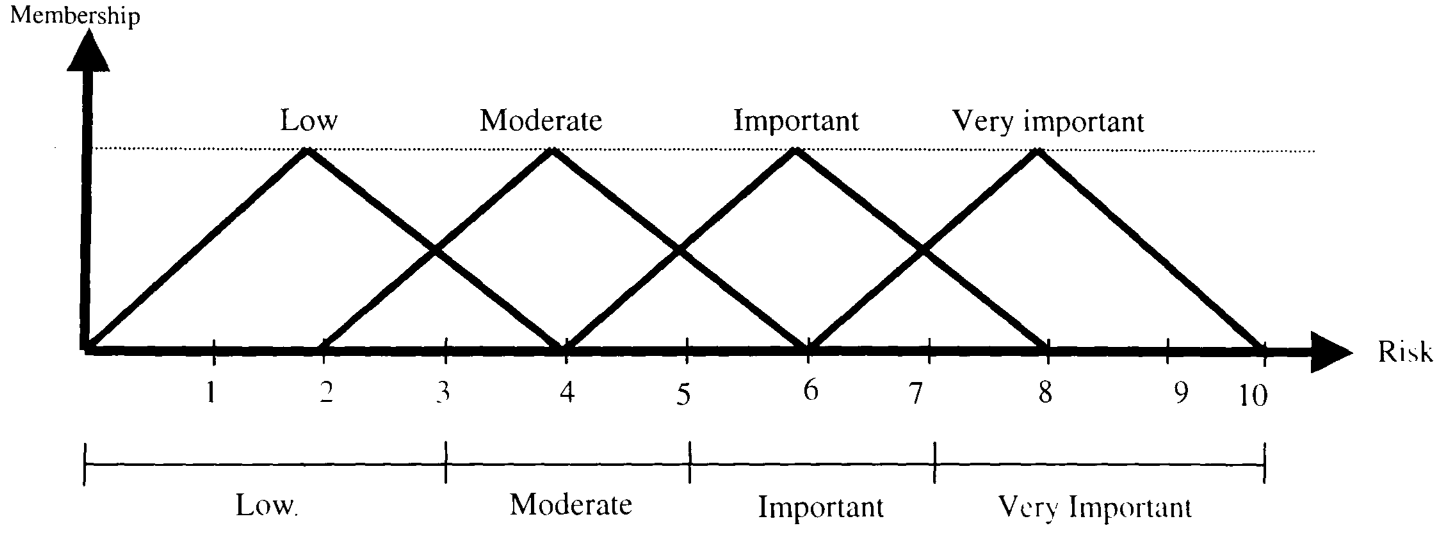


Figure 5.18 Membership function of riskiness

5.4.4 Rule Evaluation

Rules are evaluated using min-max inferencing to calculate a numerical conclusion to the linguistic rule based on their input value [Zadeh L.A., 1992]. The result of this process is called the fuzzy risk conclusion.

The 'truth value' of a rule is determined from the conjunction (i.e. minimum degree of membership of the rule antecedents) [Zadeh L.A., 1973]. Thus the truth-value of the rule is taken to be the smallest degree of truth of the rule antecedents. This truth-value is then applied to all consequences of the rule. If any fuzzy output is a consequent of more than one rule, that output is set to the highest (maximum) truth-value of all the rules that include it as a consequent. The result of the rule evaluation is a set of fuzzy conclusions that reflect the effects of all the rules whose truth-values are greater than zero.

Consider the risk priority table (table 5.2) where the probability of occurrence is '*High*' and the severity is '*Marginal*' and having a membership function of 0.6 and 1.0 respectively. Thus the conclusion Riskness = '*Important*' has a membership value of min (0.6,1.0) = 0.6. To establish how risky the hazard is, this fuzzy conclusion has to be defuzzified to obtain a single 'crisp' result.

5.4.5 Defuzzification

The defuzzification process creates a single assessment from the fuzzy conclusion set expressing the risk associated with the hazard, so that corrective actions can be prioritised. Several defuzzification techniques have been developed [Runkler T.A. and Glesner M., 1993]. One common technique is the weighted mean of maximum method, which is illustrated here. This technique averages the points of maximum possibility of each fuzzy conclusion, weighted by their degrees of truth. Hence, if the conclusion from the risk evaluation phase is, for example, 0.5 Low, 0.1 Low and 0.5 Mod, the maximum value for each linguistic term is taken. This reduces the conclusion to 0.5 Low and 0.5 Mod to be defuzzified.

The following is given to demonstrate how riskiness is obtained. Suppose Event A has the following probability of occurrence and severity of consequences:

Probability of Occurrence – **Moderate** (0.6 High, 1.0 Moderate, 0.5 Low).

Severity – **Marginal** (1.0 Marginal).

Then from the risk priority table (Table 5.2), event A will be denoted by the prefix **MM** and therefore is associated with a riskiness of '**Important'.** However, considering all the membership functions of the two parameters, i.e. probability of occurrence and severity, the following terms of riskiness are generated:

0.6 High, 1.0 Marginal = HM = 0.6 Important

1.0 Moderate, 1.0 Marginal = MM = Important

0.5 Low, 1.0 Marginal = LM = 0.5 Moderate

From figure 5.18, the support value for each linguistic term is obtained, where:

The support value for Moderate = 4

The support value for Important = 6

The support value represents an average value for a particular linguistic term.

Taking the maximum value for each term of the riskiness, that is, Important and 0.5 Moderate, the weighted mean is calculated as seen here:

$$\text{The weighted mean } (Z) = [(1.0)(6) + (0.5)(4)]/(1.0+0.5)$$
$$= 5.33$$

From this result the riskiness of event A can be prioritised as being "***Important***" with a support of **5.33.**

5.5 Application to a Hydraulic Winch System

To demonstrate the proposed approach, the data from a fishing vessel is used as a test case. The data collected for the test case is in the format of repair data. It includes:

- Voyage no (shows the date when the repair was carried out).
- Equipment repaired.
- Parts that were changed.
- Modifications that were made.
- Cause of failure (in some instances).

Specialists/contract workers carry out the repairs for this particular vessel, in the floating dock. Should a failure occur during operation at sea, temporary repair is carried out by the crew and the equipment is kept operating in the 'abnormal' condition. No records are kept of any temporary repairs done on board, however, a repair list is compiled by the Chief Engineer for the equipment to undergo permanent repair work at the next 'docking'.

In order to use this data for the modelling process, the following assumptions were made:

- Repairs and modifications are only carried out when the equipment/component has failed.
- Upon completion of repair, the equipment is assumed to be "same-as-new".

For this test case the trapezoidal function was selected and estimated. The boundaries of the trapezoidal function were determined for each set. These values being the values of x for the respective α-cuts are subjective and were predominantly based on the policies and attitude of the company and on what the company thought to be tolerable limits within which they wish to operate. To describe the probability of occurrence, linguistic terms such as "Very High", "High", "Moderate", "Low", and "Remote" are used. A range of limits quantifying the probability of occurrence is then assigned to each term. These limits are in the form of Mean Time Between Failures (MTBF). MTBF is given by:

$$MTBF = \frac{\sum t_i + \sum s_i}{n} \qquad (20)$$

where: t_i = time to failure, s_i = survival time and n = number of failures. These limits are then converted into failure rates by the following formula:

$$\lambda = \frac{1}{MTBF} \qquad (21)$$

A failure rate is calculated under the assumption that the mean down time and repair time is very small compared to the operating time. The MTBF is then converted to failure rate using equation (21) and is reflected along an ordinal scale as shown in table 5.3.

The membership function used is a trapezoidal function which, is developed using the vertical approach as explained in section 5.4.1 [Pedrycz W. and Gomide F., 1998]. This function allows a membership value of 1 for a range of probabilities unlike the triangular function. This function is thought to model the probability of occurrence close to what it is in reality. Figure 5.19 shows the membership function along with its ordinal scale. The limits and the centre point values of the ordinal scale are given by the dotted line and will be used to perform the fuzzy arithmetic.

Probability (Linguistic term)	*MTBF range (days)*	*Failure rate (ordinal scale)*
Very High	1 to 5	1 to 2 x 10^{-1}
High	5 to 50	2 x 10^{-1} to 2 x 10^{-2}
Moderate	50 to 500	2 x 10^{-2} to 2 x 10^{-3}
Low	500 to 2000	2 x 10^{-3} to 5 x 10^{-4}
Remote	2000 to 10000	5 x 10^{-4} to 1 x 10^{-5}

Table 5.3 Probability range for linguistic terms.

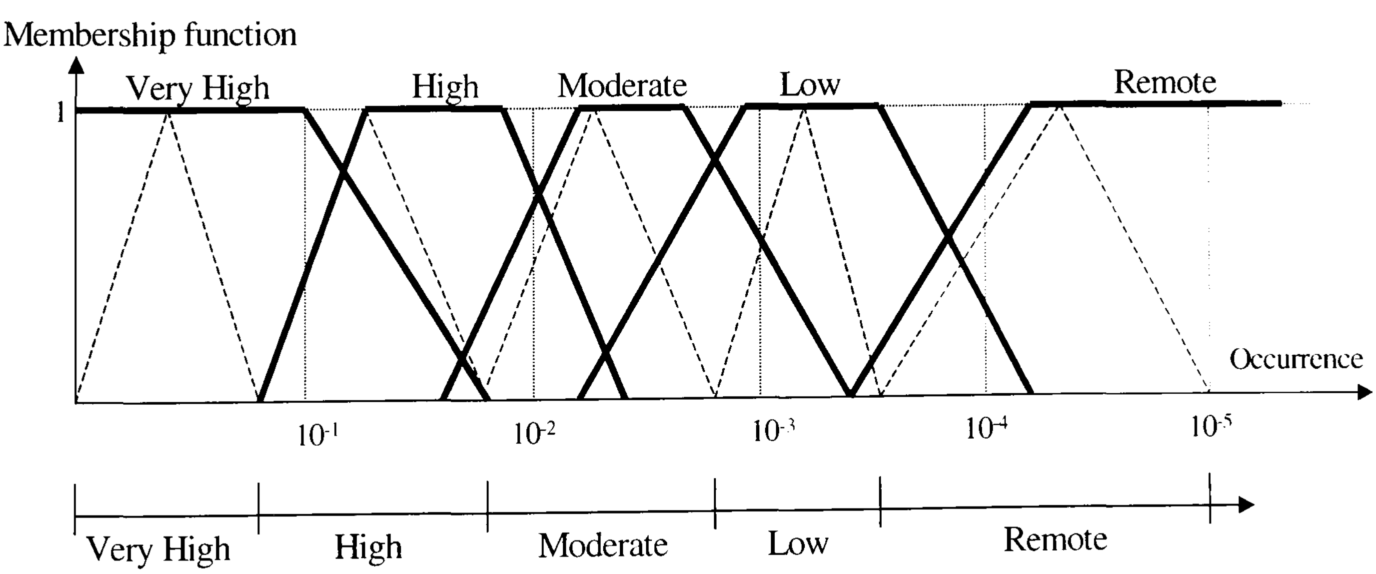


Figure 5.19 Membership function and ordinal scale

The system used to demonstrate this methodology is an operating system of a Gilson winch on board an ocean trawler. This trawler is a 1266 GRT (Gross Tonnage), deep-sea trawler with an L.O.A (length overall) of 60 meters. The Gilson winch is hydraulically operated and is situated forward of the main winches. Unlike the main winches, it does not bear the load of the catch. It serves as an auxiliary winch to the main winches.

Table 5.4 shows the failure data of the primary/basic events for a Gilson winch failure. The data collected is over a period of 66 months (14 voyages), and from this data, the linguistic term for failure probability of each basic event is determined by identifying the number of occurrences per operating day(s) on the ordinal scale. The membership function is then determined by reading off the intersecting points on the y-axis.

Basic Events	***MTBF (days)***	***Linguistic term***	***Membership function***
Pipe flange leak	900	Low	0.5 Mod, Low, 0.1 Rem
Pipe	450	Moderate	0.6 High, Mod, 0.5 Low
Control valve fail	900	Low	0.5 Mod, Low, 0.1 Rem
Filter choke	40	High	0.72 V.High, High, 0.18 Mod
Brake cylinder fail	750	Low	0.5 Mod, Low, 0.1 Rem
Brake seal fail	300	Moderate	0.6 High, Mod, 0.5 Low
Clutch cylinder fail	900	Low	0.5 Mod, Low, 0.1 Rem
Clutch seal leak	900	Low	0.5 Mod, Low, 0.1 Rem
Air cylinder fail	900	Low	0.5 Mod, Low, 0.1 Rem

Table 5.4 Probabilities of basic events for a Gilson winch failure

The fault tree shown in Figure 5.20 is generated from the data collected for the failure of the Gilson winch. Each secondary or intermediate event (e.g. brake failure, clutch failure, hydraulic leakage, etc) is modelled by gathering the available failure data and then grouping them according to the component or system they affect. For example, the failure of the brake cylinder (GBCyl) and brake seal leakage (GBSeal) will cause the brake to fail. Hence, the brake failure (G.Brake) is the secondary event with the GBCyl and GBSeal being its basic events. To demonstrate the application of this methodology with an example, the fault tree used only traces the path of failures that have been known to occur in the past, rendering the system inoperable.

Take two basic events from the fault tree in figure 5.20, GBCyl and GBSeal as an example. The occurrence rates for GBCyl and GBSeal are 1 failure in 750 days and 1 failure in 300 days respectively. Therefore event GBCyl would have a fuzzy probability of *Low* and GBSeal, *Moderate*. Performing the arithmetic operation using Equations (13), (15) and (16) on both these events will yield the result of 0.62 *High*, *Moderate* and 0.46 *Low* for the secondary event, brake failure (G.Brake). Figure 5.21 shows a graphical representation of this. This can be interpreted as the secondary event belonging to the linguistic term *High* with a membership of 62%, complete membership (100%) to *Moderate* and *Low* with a membership of 46%. Similarly, all the basic events in the fault tree are analysed in this manner producing an end result for the top event. The Gilson winch failure has a fuzzy failure probability of *HIGH* with a membership function of 0.9 Very High, 0.84 High and 0.1 Moderate. Although the membership to the *Very High* linguistic term is the highest, when the result is defuzzified to reflect the range of probability which it belongs to, it falls into the *High* category on the ordinal scale. It can therefore be stated that the failure rate of the gilson winch lies between 2 x 10^{-1} and 2 x 10^{-2}.

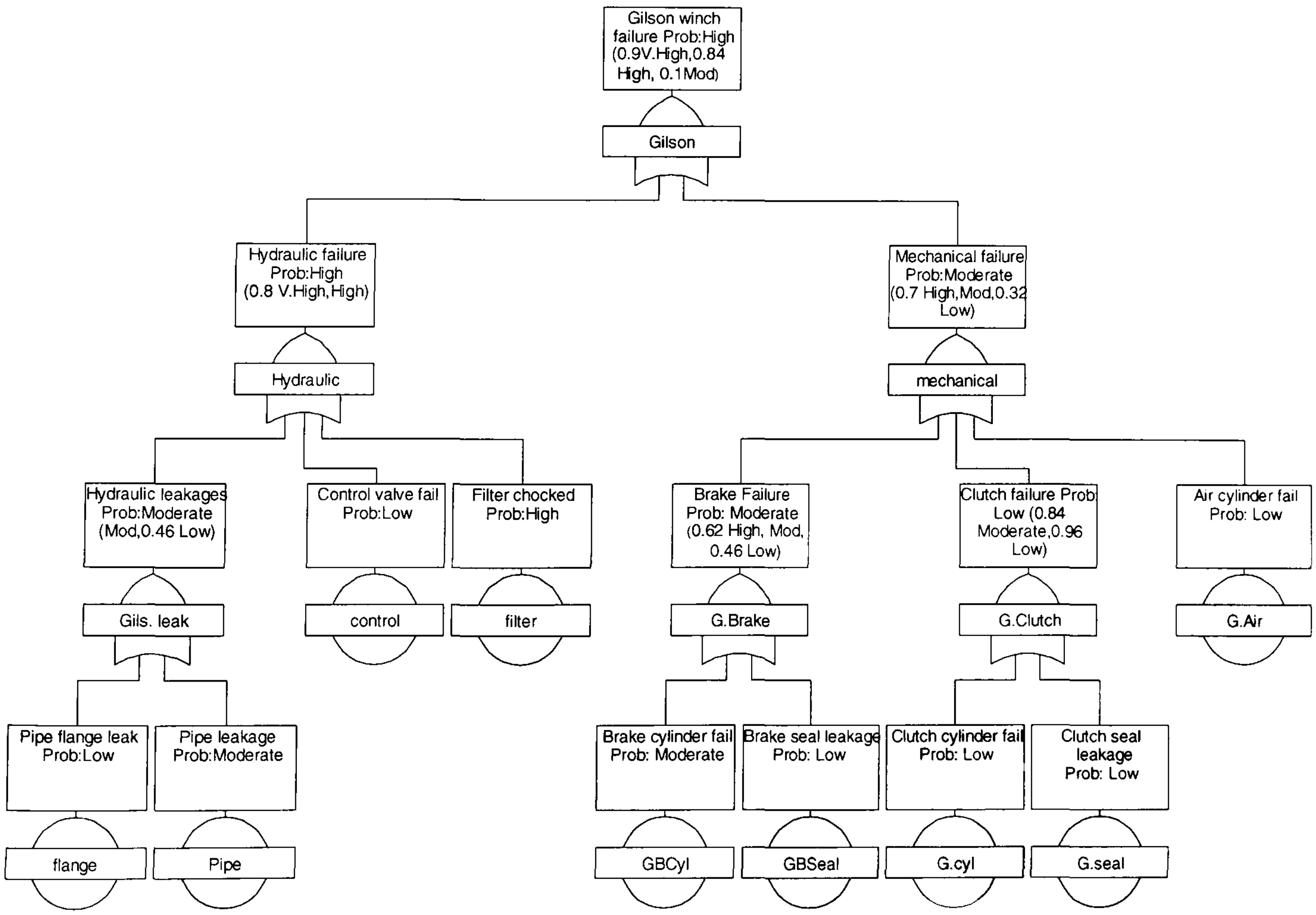


Figure 5.20 Fault tree of Gilson winch failure

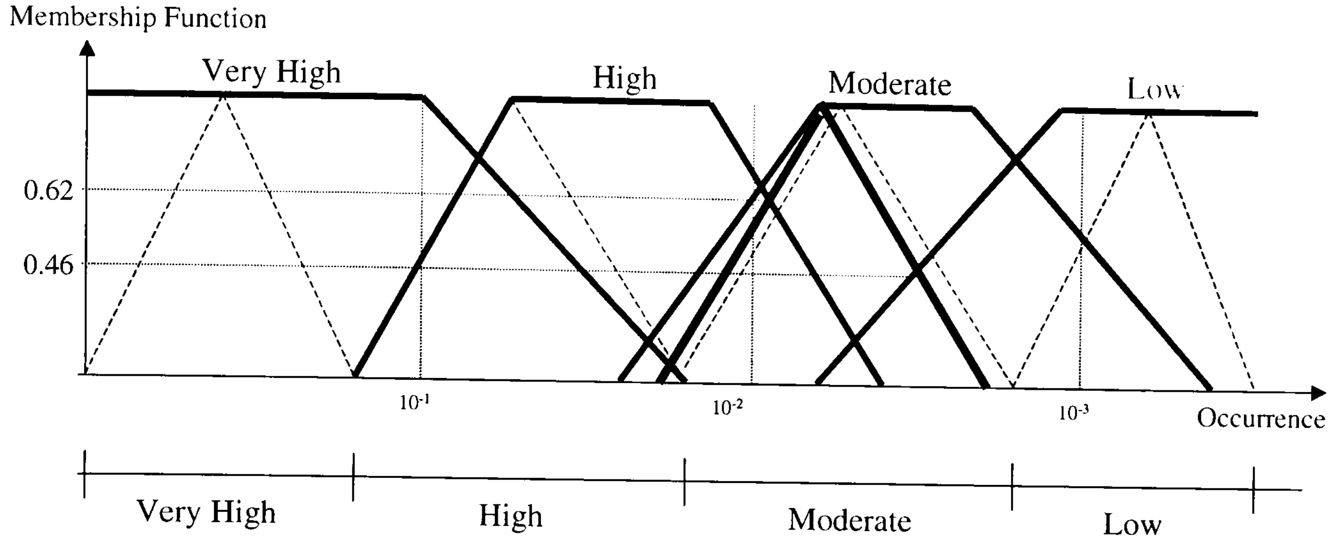


Figure.5.21 Graphical representation of fuzzy arithmetic operation on two basic events

5.5.1 Severity of consequences modelling

The amount of data that was available on the consequences of a failure was scarce and difficult to come by. However, much of the data was in terms of cost and reports of accidents and incidents that led to injuries. Since there is no standard format for reporting an accident, the data was obtained from telexes, faxes, superintendent reports, Chief Engineers' logbook and various other sources. To complement the data, expert knowledge and judgement was used to assign ratings to each group (Personnel, Environment, Equipment and Catch). Table 5.5 shows the analyses of various failures in a Gilson winch system.

	Personn.	*Environ.*	*Equip.*	*Catch*	*Total*	*HC*	**Membership function**
Pipe Flange leak	1	2	1	1	**5**	**2**	0.8 Neg, 0.6 Marg.
Pipe leak	1	2	1	1	**5**	**2**	0.8 Neg, 0.6 Marg.
Control v/v fail	1	1	2	3	**7**	**3**	0.8 Crit., 0.2 Cat.
Filter choke	1	1	1	3	**6**	**3**	0.5 Marg.,Crit.
Brake cyl fail	1	1	3	3	**8**	3	0.5 Crit., 0.5Cat.
Brake seal leak	1	1	2	2	**6**	**2**	Marg., 0.2 Crit.
Clutch cyl fail	1	1	3	3	**8**	**3**	0.5 Crit., 0.5Cat.
Clutch seal leak	1	1	2	2	**6**	**2**	Marg., 0.2 Crit.
Air cyl fail	1	1	1	1	**4**	**1**	Neg.

Table 5.5 Gilson winch severity of consequence

5.5.2 Risk ranking of the hydraulic winch system

The probability of occurrence is determined for each basic event (table 5.4) and the severity of the same basic events is as shown in table 5.5. The risk estimation and ranking of these basic events can be carried out. For the pipe flange leak event, the probability of occurrence was determined to be 0.5 *Mod, Low* and 0.1 *Rem*, and the severity as 0.8 *Neg* and 0.6 *Marg*. Using the rule evaluation method described in section 5.5.4 and 5.5.5, which is summarised here in table 5.6, the linguistic term for risk is determined.

From table 5.6, the risk evaluation for the pipe flange failure can be summarised as being (0.5 Low, 0.5 Imp, 0.8 Low, 0.6 Mod, 0.1 Low and 0.1 Low). Using the minimum-maximum inferencing, this can be reduced to 0.8 Low, 0.6 Mod and 0.5 Imp. The number 0.8, 0.6 and 0.5 represents the degree of belief and not the membership function of the particular linguistic term. Similarly, the risk evaluation for all other basic events is carried out. The results of the evaluation are shown in table 5.7.

Probability of occurrence	***Severity***	***Risk***
0.5 Moderate	0.8 Negligible	0.5 Low
0.5 Moderate	0.6 Marginal	0.5 Important
Low	0.8 Negligible	0.8 Low
Low	0.6 Marginal	0.6 Moderate
0.1 Remote	0.8 Negligible	0.1 Low
0.1 Remote	0.6 Marginal	0.1 Low

Table 5.6 Risk evaluation for pipe flange failure

Weighted mean for event pipe flange leak is calculated as follows:

$$Z = \frac{\mathbf{(0.8\,x\,2) + (0.6\,x\,4) + (0.5\,x\,6)}}{\mathbf{(0.8 + 0.6 + 0.5\,)}} = \mathbf{3.68}.$$

Therefore from figure 5.18, the pipe flange leak event will be prioritised by "**Moderate**" with a support value of **3.68**. Similarly, the weighted mean can be calculated for all the other events within the system. Table 5.8 shows the results of these calculations.

Events	*Occurrence*	*Severity*	*Risk*
Pipe Flange leak	0.5 Mod, Low, 0.1 Rem	0.8 Neg, 0.6 Marg	0.8 Low, 0.6 Mod, 0.5 Imp
Pipe leak	0.6 High, Mod, 0.5 Low	0.8 Neg, 0.6 Marg	0.8 Low, 0.6 Mod, 0.6 Imp
Control v/v fail	0.5 Mod, Low, 0.1 Rem	0.8 Crit, 0.2 Cat	0.2 Mod, 0.8 Imp, 0.2 V.Imp
Filter choke	0.72 V.High, High, 0.18 Mod	Crit, 0.5 Marg	0.5 Imp, V.Imp
Brake cyl fail	0.5 Mod, Low, 0.1 Rem	0.5 Crit, 0.5 Cat	0.1 Mod, 0.5 Imp, 0.5 V.Imp
Brake seal leak	0.6 High, Mod., 0.5 Low	Marg, 0.2 Crit	0.5 Mod, Imp, 0.2 V.Imp
Clutch cyl fail	0.5 Mod, Low, 0.1 Rem	0.5 Crit, 0.5 Cat	0.1 Mod, 0.5 Imp, 0.5 V.Imp
Clutch seal leak	0.5 Mod, Low, 0.1 Rem	Marg, 0.2 Crit	0.1 Low, Mod, 0.5 Imp
Air cyl fail	0.5 Mod, Low, 0.1 Rem	Neg	Low

Table 5.7 Risk evaluation of gilson winch basic events

Event	*Risk (Linguistic term)*	*Support value*
Filter choke	**Very Important**	**7.33**
Clutch cyl fail	**Important**	**6.72**
Brake cyl fail	**Important**	**6.72**
Control v/v fail	**Important**	**6.00**
Brake seal leak	**Important**	**5.65**
Clutch seal leak	**Moderate**	**4.50**
Pipe leak	**Moderate**	**3.68**
Pipe flange leak	**Moderate**	**3.68**
Air cyl fail	**Low**	**2.00**

Table 5.8 Defuzzified ranking of a gilson winch failure events

5.6 Conclusion

Lack of reliable safety data and lack of confidence in safety assessment have been two major problems in safety analysis of various engineering activities. This is particularly true in FSA due to the fact that the level of uncertainty is high. In ship safety assessment it may often be difficult to quantify the probability of undesired events occurring and the associated consequences of effect due to this very reason.

The proposed approach addresses these concerns and offers an alternative solution. Its application can be extended to sub-systems within an operating system to generate a list of components, which are ranked according to their priority for attention. This can help the owners and operators of fishing vessels to improve operating and maintenance strategies. This approach can be adopted within the FSA framework for generic ships and the results obtained from the analysis can be further utilised in step 4 of the FSA [Marine Safety Agency, 1993]. As the proposed approach employs the fault tree method, it can be integrated at the hazard identification stage of a safety assessment as a preliminary fault tree. The analysis can then be carried forward to include quantification using linguistic terms for the probability of occurrence and severity of consequences. Due to the fact that precision is not forced, it would be appealing to use this method for fishing vessels as reliable safety data is scarce and hard to come by.

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CHAPTER 6

MODIFIED FAILURE MODE AND EFFECTS ANALYSIS

Summary

The marine industry is recognising the powerful techniques that can be used to perform risk analysis of marine systems. One technique that has been applied in both national and international marine regulations and operations is Failure Mode and Effects Analysis (FMEA). This risk analysis tool assumes a failure mode occurs in a system/component through some failure mechanism, the effect of this failure is then evaluated. A risk ranking is produced in order to prioritise the attention for each of the failure modes identified. The traditional method utilises the Risk Priority Number (RPN) ranking system. This method determines the RPN by finding the multiplication of factor scores. The three factors considered are probability of failure, severity and detectability. Traditional FMEA has been criticised to have several drawbacks. These drawbacks are addressed in this chapter. A new proposed approach, which utilises the fuzzy rules base and grey relation theory is presented.

6.1 Introduction

Failure Mode and Effects Analysis (FMEA) is intended to provide information for making risk management decisions. Detail procedures on how to carry out an FMEA and its various application in the different industries have been documented by Stamatis [Stamatis D.H., 1995]. A brief introduction to this method of analysis is presented in chapter 3 (section 3.11).

Over the years several variations of the traditional FMEA have been developed. Russomano and Price discusses the use of knowledge base system for the automation of the FMEA process [Russomano D.J. et. al., 1992; Price C.J. et. al., 1992; Price C.J. et. al., 1995]. The use of a causal reasoning model for FMEA is documented by Bell [Bell

D. et. al., 1992]. An improved FMEA methodology, which uses a single matrix to model the entire system and a set of indices derived from probabilistic combination to reflect the importance of an event relating to the indenture under consideration and to the entire system is presented by Kara-Zaitri [Kara-Zaitri C. et. al., 1991; Kara-Zaitri C. et. al., 1992]. A similar approach was made to model the entire system using a fuzzy cognitive map [Pelaez C.E. and Bowles J.B., 1996].

Many FMEAs have a quantitative objective, that is, to predict the likelihood of certain types of system failures. This requires good information on the statistical distribution of component failures. It also requires knowledge of dependency relationships among components under normal operations and under external perturbations.

FMEA can also be used as part of a qualitative analysis (or a semi-quantitative analysis). It attempts to identify critical components whose failure will lead to accident, injury, and/or property loss. The goal is to make systems safer or more reliable by:

- Evaluating the effects of component failures on system performance.
- Identifying those components that are critical to safety.
- Developing system enhancements or administrative changes to improve safety and/or system reliability.

The major safety-related objectives of FMEA include:

- Analysis of the system to determine effects of component failures on system performance and safety.
- Identification of components that are critical to safety (identifying where component failure would compromise system operation, resulting in injuries, property damage, or other losses).
- Redesigning the system to improve "passive" reliability and safety.
- Improving maintenance routines to reduce the likelihood of component failures.

FMEA is used to assist analysts to perform hazard analyses and it is regarded as a supplement rather than a replacement for hazard analyses. Safety analysts can use the FMEA to verify that all safety critical hardware has been addressed in the hazard analyses. The FMEA in hardware systems is an important technique for evaluating the design and documenting the review process. All credible failure modes and their resultant effects at the component and system levels are identified and documented. Items that meet defined criteria are identified as critical items and are placed on the Critical Item List (CIL). Each entry of the CIL is then evaluated to see if design changes can be implemented so that the item can be deleted from the CIL. Items that cannot be deleted from the CIL must be accepted by the program/project, based on the rationale for acceptance of the identified risk. The analysis follows a well-defined sequence of steps that encompass (1) failure mode (2) failure effects (3) causes (4) detectability (5) corrective or preventive actions and (6) rationale for acceptance.

6.1.1 FMEA procedure

The process for carrying out an FMEA can be divided into several steps as seen in figure 6.1. These steps are briefly explained here:

1. Develop a good understanding of what the system is supposed to do when it is operating properly.
2. Divide the system into sub-systems and/or assemblies in order to "localise" the search for components.
3. Use blue prints, schematics and flow charts to identify components and relations among components.
4. Develop a complete component list for each assembly.
5. Identify operational and environmental stresses that can affect the system. Consider how these stresses might affect the performance of individual components.
6. Determine failure modes of each component and the effects of failure modes on assemblies, sub-systems, and the entire system.
7. For each failure mode, establish detectability (dependent upon several elements including alarm/monitoring devices in place)
8. Categorise the hazard level (severity) of each failure mode (several qualitative systems have been developed for this purpose).

List of Tables

9. Estimate the probability. In the absence of solid quantitative statistical information, this can also be done using qualitative estimates.
10. Calculate the Risk Priority Number (RPN): the RPN is given as the multiplication of the index representing the probability, severity and detectability.
11. Determine if action needs to be taken depending on the RPN.
12. Develop recommendations to enhance the system performance. These fall into two categories:
    - Preventive actions: avoiding a failure situation.
    - Compensatory actions: minimising losses in the event that a failure occurs.
13. Summarise the analysis: this can be accomplished in a tabular form.

Generally, an FMEA table will have a major row for each component. As these components may have multiple failure modes, the major row is sometimes divided into sub-rows where each sub-row summarises a specific failure mode. The table is organised into the following columns:

a. Component - create a major row for each component.
b. Failure mode(s) - identify failure modes and establish a sub-row for each mode.
c. Effects (by failure mode) - describe the effects on safety and system performance resulting from the failure. List specific adverse outcomes.
d. Probability - if reliability data does not exist, estimate using qualitative ranks.
e. Hazard level (severity) - if experience data does not exist, estimate using qualitative ranks.
f. Causes of failure mode (if known) - this includes environmental and/or operational stresses that increase the likelihood of the failure mode.
g. Methods of detecting failure mode (if known) - although this entry does not prevent a failure from occurring, it is important to discover that a failure has occurred. This column is used to present signs and symptoms that a component has failed.
h. Suggested interventions - hardware modifications and/or compensatory actions to minimise effects

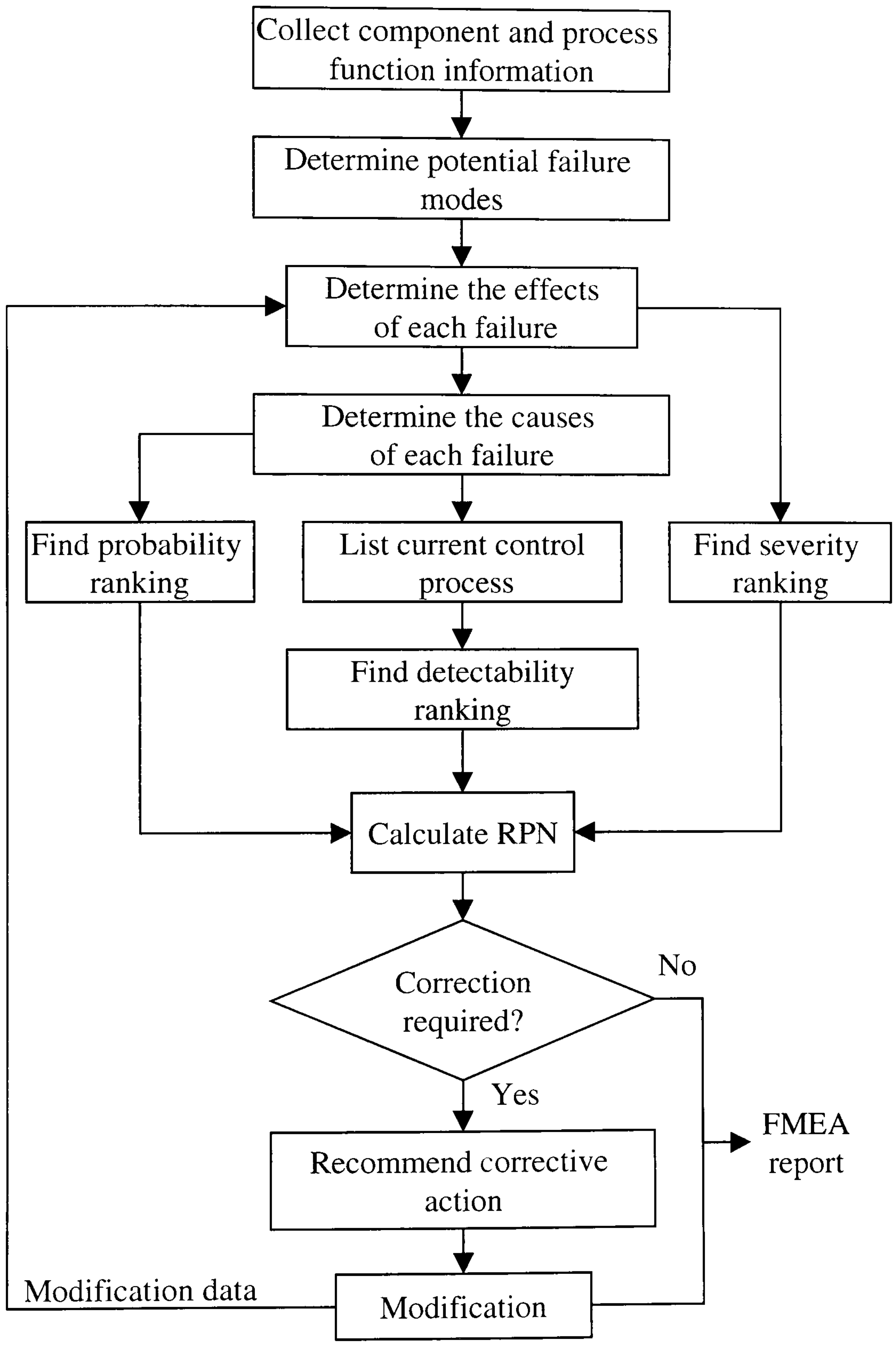

Figure 6.1 FMEA process

6.1.2 Terminology in FMEA

Although there have been many variations of the FMEA, the terminology used throughout the years has been maintained. Some of the common terms used in an FMEA include:

Failure mode: Failure modes are sometimes described as categories of failure. A potential failure mode describes the way in which a product or process could fail to perform its desired function (design intent or performance requirements) as described by the needs, wants, and expectations of the internal and external customers /users. Examples of failure modes are: fatigue, collapse, cracked, performance deterioration, deformed, stripped, worn (prematurely), corroded, binding, seized, buckled, sag, loose, misalign, leaking, falls off, vibrating, burnt, etc.

Potential cause(s) of failure: This is a list conceivable potential cause(s) of failure assignable to each failure mode. The causes listed should be concise and as complete as possible. Typical causes of failure are: incorrect material used, poor weld, corrosion, assembly error, error in dimension, over stressing, too hot, too cold, bad maintenance, damage, error in heat treat, material impure, forming of cracks, out of balance, tooling marks, eccentric, etc.

Severity: Severity is an assessment of how serious the effect of the potential failure mode is on the customer/user.

Effect: An effect is an adverse consequence that the customer/user might experience. The customer/user could be the next operation, subsequent operations, or the end user.

6.2 Setbacks of FMEA

The traditional FMEA has been a well-accepted safety analysis method, however, it suffers from several setbacks. One of the critically debated setbacks, is the method that the traditional FMEA employs to achieve a risk ranking. The purpose of ranking risk in order of importance is to assign the limited resources to the most serious risk items. Traditional FMEA uses a RPN to evaluate the risk level of a component or process. The RPN is obtained by finding the multiplication of three factors, which are the probability of failure (S_f), the severity of the failure (S) and the probability of not detecting the failure (S_d). Representing this mathematically will give:

$$RPN = S_f \ x \ S \ x \ S_d \qquad (1)$$

Tables 6.1, 6.2 and 6.3 list the scales used to measure the three factors given in equation (1).

Probability of Occurrence	***Rating***	***Possible failure rate (Operating days)***
Remote	1	< 1:20000
Low	2 3	1:20000 1:10000
Moderate	4 5 6	1:2000 1:1000 1:200
High	7 8	1:100 1:20
Very High	9 10	1:10 1:2

Table 6.1 Traditional FMEA scale for probability of occurrence (S_f)

Severity	***Rating***
Negligible	1
Low	2 3
Moderate	4 5 6
High	7 8
Very High	9 10

Table 6.2 Traditional FMEA scale for severity (S)

Detectability	***Rating***	***Probability (%) of detection***
Very High	1	86-100
High	2	76-85
	3	66-75
Moderate	4	56-65
	5	46-55
	6	36-45
Low	7	26-35
	8	16-25
Remote	9	6-15
	10	0-5

Table 6.3 Traditional FMEA scale for detectability (S_d)

These tables show that the traditional FMEA uses five scales and scores of one to ten, to measure the probability of occurrence, severity and the probability of detection. Though this simplifies the computation, converting the probability into another scoring system, and then finding the multiplication of factor scores are believed to cause problems. From tables 6.1 and 6.3 it can be seen that the relation between S_f and the probability scale is non-linear, while it is linear for that between S_d and the probability scale.

The most critically debated disadvantage of the traditional FMEA is that various sets of S_f, S and S_d may produce an identical value of RPN, however, the risk implication may be totally different [Gilchrist W., 1993; Ben-Daya M. and Raouf A., 1993]. For example, consider two different events having values of 2,3,2 and 4,1,3 for S_f, S and S_d respectively. Both these events will have a total RPN of 12 (RPN_1 = 2x3x2 = 12 and RPN_2 = 4x1x3 = 12), however, the risk implications of these two events may not necessarily be the same. This could entail a waste of resources and time or in some cases a high risk event going unnoticed.

The other prominent disadvantage of the RPN ranking method is that it neglects the relative importance among S_f, S and S_d. The three factors are assumed to have the same importance. This may not be the case when considering a practical application of the FMEA process.

An approach using fuzzy rule base and grey relation theory is proposed to address these setbacks. A fuzzy rule base is used to rank the potential causes identified within the FMEA, which would have identical RPN values but different risk implications. The approach then extends the analysis to include weighting factors for S_f, S and S_d using defuzzified linguistic terms and grey relation analysis. The background of fuzzy set theory has been explained in chapter 5 (section 5.3) and the principle of grey relation theory is briefly described in section 6.3.

6.3 Background of Grey Theory

Grey system theory was proposed and developed by Deng in 1982 (Deng J., 1982; Deng J., 1989). In grey systems, the information, such as operation, mechanism, structure and behaviour, are neither deterministic nor totally unknown, but are partially known. It explores system behaviour using relation analysis and model construction. It also deals with making decisions characterised by incomplete information (Shih K.C. et. al., 1996; Wu H.H. et. al., 1984).

Grey system theory has been widely used in many fields, such as optimisation [Zheng Y. and Lewis R.W., 1993], engineering [Wu J.R. and Ouhyoung M., 1994], geomechanics [Zheng Y., 1988], economy [Jianer H., 1987], history [Junjiang H., 1986], geography [Li H., 1991], traffic [Senra L., 1986], management [Deng J., 1986] and so on.

The use of grey theory within the FMEA framework can be accomplished [Chang C.L. et. al., 1999]. The method involves several steps, which are briefly discussed here. First, a comparative series, which reflects the various linguistic terms and decision factors of the study, is generated The linguistic terms describing the decision factors are for example, *Low, Moderate, High,* etc. The comparative series can be represented in a form of a matrix as shown in equation (2). This matrix shows the failure modes, $\{x_1, x_2, \ldots\ldots x_n\}$ and the linguistic terms describing each decision factor of the failure mode, $\{x_1(1), x_1(2), \ldots x_1(k)\}$, $\{x_2(1), x_2(2), \ldots x_2(k)\}$, etc.

$$x = \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{bmatrix} = \begin{bmatrix} x_1(1) & x_1(2) & . & . & . & x_1(k) \\ x_2(1) & x_2(2) & . & . & . & x_2(k) \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ x_n(1) & x_n(2) & . & . & . & x_n(k) \end{bmatrix} \qquad (2)$$

The standard series is an objective series that reflects the ideal or desired level of all the decision factors and can be expressed as $x_O = [x_O(1),. x_O(2),.... x_O(k)]$. This could be assumed to be the lowest level of the linguistic terms describing the decision factors. The difference between the two series, D_O, (comparative and standard series) is calculated. The grey relation coefficient is obtained using equation (3):

$$\gamma(x_0(k), x_i(k)) = \frac{\min\limits_i \min\limits_k |x_0(k) - x_i(k)| + \zeta \max\limits_i \max\limits_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \zeta \max\limits_i \max\limits_k |x_0(k) - x_i(k)|} \qquad (3)$$

where $x_O(k)$ is the min or max value (as defined in equation (3)) from the standard series and $x_i(k)$ is the min or max value (as defined in equation (3)) from the comparative series and ζ is an identifier, $\zeta \in (0,1)$, only affecting the relative value of risk without changing the priority [Hong G., 1986].

To find the degree of relation, the weighting coefficient (β_k) of the decision factors must first be decided. For the application of the grey theory to FMEA, β_k should be set to suit the intention of the FMEA and comply with equation (4).

$$\sum_{k=1}^{n} \beta_k = 1 \qquad (4)$$

The degree of relation, $\Gamma(x_i, x_j)$, can then be calculated using equation (5).

$$\Gamma(x_i, x_j) = \sum_{k=1}^{n} \beta_k \gamma\{x_i(k), x_j(k)\} \qquad (5)$$

The degree of relation in FMEA denotes the relationship between the potential causes and the optimal value of the decision factors. The higher the value obtained from equation (5), the smaller the effect of the identified events. Therefore, the increasing order of the degree of relation represents the risk priority of the identified areas that are to be improved.

6.4 Proposed Fuzzy Rule Base Approach

The aim of this approach is to develop a method that does not require a utility function to define the probability of occurrence (S_f), severity (S) and detectability (S_d) considered for the analysis and to avoid the use of the traditional RPN. This is achieved by using information gathered from experts and integrating them in a formal way to reflect a subjective method of ranking risk.

The flowchart in figure 6.2 illustrates the proposed fuzzy set approach for the modified FMEA process. The first step is to set up the membership function of the three categories, that is, probability of occurrence (S_f), severity (S) and detectability (S_d). Once the membership functions of these three categories have been developed, the FMEA is carried out in the traditional manner with the use of brainstorming techniques [Brahm C. and Kleiner B.H, 1996; VanGundy A., 1998]. Each of the failure modes is then assigned a linguistic term representing the three linguistic variables, (probability of occurrence, severity and detectability). Using the fuzzy rule base generated, these three variables are integrated to produce linguistic terms representing the "*priority for attention*". This term represents the risk ranking of all the failure modes identified for the components. Once a ranking has been established, the process then follows the traditional method of determining the corrective actions and generating the FMEA report.

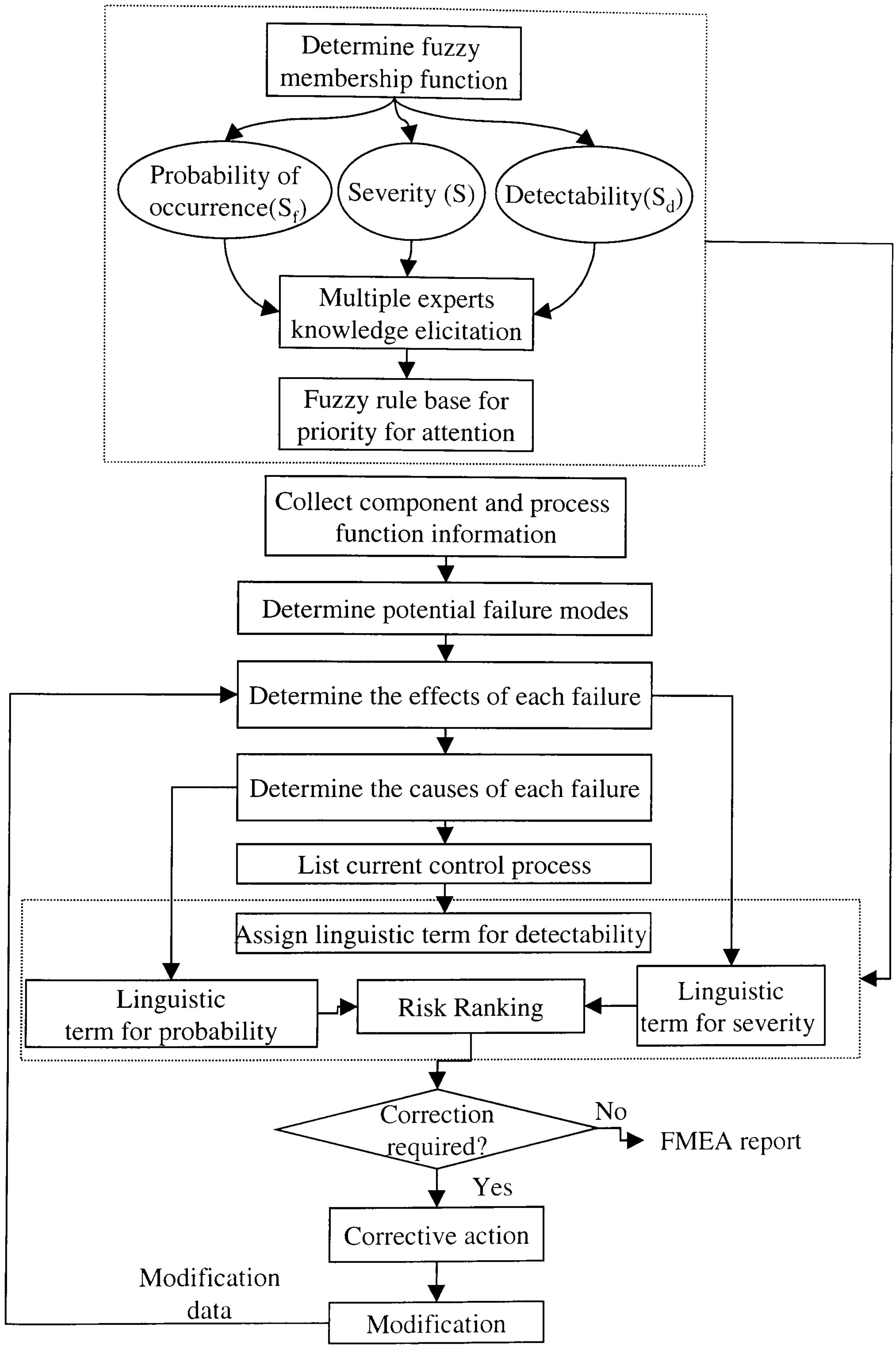

Figure 6.2 Flowchart of proposed fuzzy rule base approach

6.4.1 Fuzzy membership function

The fuzzy membership function is developed for each of the three variables using multiple experts. These experts should be appropriately chosen so as to ensure realistic and non-biased membership functions [Kuusela H. et. al., 1998]. The application of the modified FMEA to fishing vessels requires experts who are familiar with the operation and management circumstances of the industry. Using the selected experts, the fuzzy sets and membership functions can be generated as explained here.

Assume that n experts are asked for some $x \in X$ to evaluate the proposition "x belongs to A" as either true or false, where A is a fuzzy set on X that represents a linguistic term associated with a given linguistic variable. Given a particular element $x \in X$, let $a_i(x)$ denote the answer of expert i ($i \in N_n$). Assume that $a_i(x) = 1$ when the proposition is valued by expert i as true, and $a_i(x) = 0$ when it is valued as false [Klir G.J. and Yuan B., 1995]. Then,

$$A(x) = \frac{\sum_{i=1}^{n} a_i(x)}{n} \qquad (6)$$

may be viewed as a probabilistic interpretation of the constructed membership function. When the experts have different degrees of competencies, C_i, with regard to the model being constructed, equation (6) is modified to give:

$$A(x) = \sum_{i=1}^{n} C_i a_i(x) \qquad (7)$$

where

$$\sum_{i=1}^{n} C_i = 1 \qquad (8)$$

The degree of competency for each of the experts should be determined based on their experience and knowledge of fishing vessels and should be agreed upon by all the experts involved in the study.

In the fuzzy rule base analysis, the linguistic variable is determined to be the probability of occurrence (S_f), the severity (S) and the detectability (S_d). Each of the three linguistic variables has five linguistic terms describing them. These linguistic terms are *Remote, Low, Moderate, High* and *Very High* (for simplicity, the term *Negligible* for the Severity category is substituted by *Remote).* The interpretations of these linguistic terms are given in table 6.4. This information can also be represented graphically as seen in figure 6.3, where it was developed by a collective agreement between the analysts involved in the study. Each expert was asked for the values (on the x-axis) that they thought belonged to the appropriate linguistic term. The membership functions for the linguistic terms proposed were determined using equation (7).

Linguistic term	***Probability of occurrence***	***Severity***	***Detectability***
Remote	It would be very unlikely for these failures to be observed even once	A failure that has no effect on the system performance, the operator will probably not notice	Defect remains undetected until the system performance degrades to the extent that the task will not be completed
Low	Likely to occur once, but unlikely to occur more frequently	A failure that would cause slight annoyance to the operator, but that would cause no deterioration to the system	Defect remains undetected until system performance is severely reduced
Moderate	Likely to occur more than once	A failure that would cause a high degree of operator dissatisfaction or that causes noticeable but slight deterioration in system performance	Defect remains undetected until system performance is affected
High	Near certain to occur at least once	A failure that causes significant deterioration in system performance and/or leads to minor injuries	Defect remains undetected until inspection or test is carried out
Very High	Near certain to occur several times	A failure that would seriously affect the ability to complete the task or cause damage, serious injury or death	Failure remains undetected, such a defect would almost certainly be detected during inspection or test

Table 6.4 Interpretations of the linguistic terms

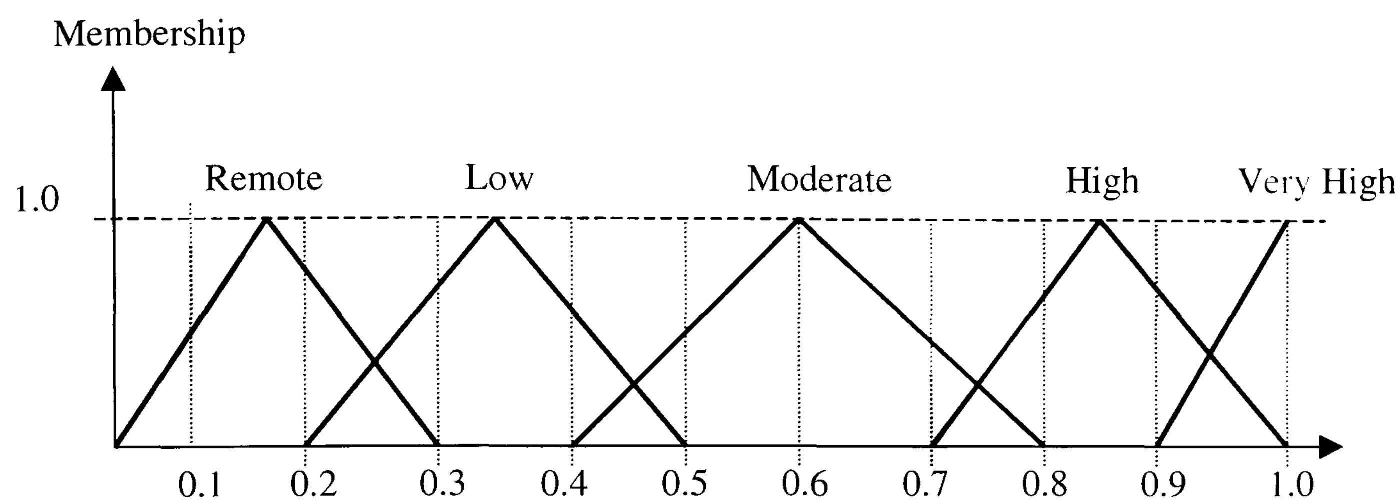

Figure 6.3 Graphical representation of the membership function for the linguistic terms

6.4.2 Fuzzy rule base development

Fuzzy logic systems are knowledge-based or rule-based systems constructed from human knowledge in the form of fuzzy *IF-THEN* rules [Wang L.X., 1997]. An important contribution of fuzzy system theory is that it provides a systematic procedure for transforming a knowledge base into non-linear mapping. A fuzzy *IF-THEN* rule is an *IF-THEN* statement in which some words are characterised by continuos membership functions.

IF-THEN rules have two parts: an antecedent that is compared to the inputs and a consequent, which is the result/output. The input of the fuzzy rules base is the probability of occurrence, severity and detectability. The output of the FMEA is assigned a linguistic variable, *priority for attention*, and is described linguistically by *Low, Fairly Low, Moderate, Fairly High* and *High.*

In order to generate the fuzzy rule base for the FMEA, the selected experts are asked to group the various combinations of linguistic terms describing the three factors considered into a category reflecting the priority for attention. Since there are three factors and five linguistic terms describing each factor, the total number of rules are 125. However, some of these rules can be combined to reduce the number of rules of the fuzzy rule base. A typical rule from the rule base would read as:

"If failure probability is *Remote*, severity is *Remote* and detectability is *Low*, then priority for attention is *Low.*"

Using equation (7), the membership function for the rules in the fuzzy rule base can be determined. The rule base is then used in the FMEA to ascertain the priority for attention for each of the potential causes identified.

6.4.3 Ranking the priority for attention

The defuzzification process creates a single assessment from the fuzzy conclusion set expressing how corrective actions can be prioritised. Several defuzzification techniques have been developed [Runkler T.A. and Glesner M., 1993]. One common technique is the weighted mean of maximum method (WMoM), which is illustrated here. This technique averages the points of maximum possibility of each fuzzy conclusion, weighted by their degrees of truth [An M. et. al., 2000a; An M. et. al., 2000b].

Assume the output of the FMEA is assigned a linguistic variable, *priority for attention*, and is described linguistically by *Low, Fairly Low, Moderate, Fairly High* and *High.* The support value for each of these linguistic terms is determined by taking the weighted average of the support values given by each expert. Suppose the support values for the five linguistic terms are calculated on an arbitrary scale of 1 to 10 and are defined as follows: *Fairly Low* - 0.055, *Low* - 0.461, *Moderate* - 0.911, *Fairly High* - 2.041 and *High* - 7.111.

Suppose the potential cause identified in the FMEA has the following probability of occurrence, severity and detectability: Probability of Occurrence – ***Remote***, Severity – ***Remote,*** and Detectability - ***Moderate.*** Referring to the rule base, the priority of attention is for example, ***Low, 0.06 Fairly Low*** with a support value of 0.055 and 0.461 respectively. Using the WMoM method, the weighted mean, (Z), can be calculated as:

$$Z = [(1.0)(0.055) + (0.06)(0.461)]/(1.0+0.06) = 0.0780$$

From this result the priority for attention of this particular event can be numerically expressed as being **0.0780**. This method of defuzzification has been discussed in chapter 5 (section 5.4.5). Similarly all the potential causes identified in the FMEA can be analysed in this manner to produce a ranking such that the highest value of the defuzzified conclusion reflects the highest priority for attention.

6.5 Proposed Grey Theory Approach

The flowchart in figure 6.4 illustrates the proposed grey theory approach to rank the events, which are identified in the FMEA process. The first step is to set up the membership function of the three categories (probability of occurrence (S_f), severity (S) and detectability (S_d)). This can be carried out as explained in section 6.4. In order to preserve consistency in the analysis, the membership functions estimated in section 6.4.1 is preserved and applied here. Hence, each of the linguistic variables, that is, the probability of occurrence, severity and detectability will have five linguistic terms describing them. Upon identifying all the failure modes and causes of failure using brainstorming techniques (as used in the traditional FMEA process), the probability of occurrence, severity and detectability are assigned linguistic terms accordingly.

Upon assigning the appropriate linguistic term to describe each linguistic variable (for each event), the next step requires a crisp number to be produced representing each of the linguistic terms assigned. In short, the application of these fuzzy sets with grey theory requires the defuzzification of the membership functions obtained in figure 6.3 [Chang C.L. et. al., 1999]. The defuzzified values of each of the linguistic terms are used to generate the comparative series, which is represented in the form of a matrix.

At this stage, the standard series for the variables are generated by determining the optimal level of all three variables for the events in the FMEA. This standard series is also represented in the form of a matrix. The difference between the standard and comparative series is obtained and the results are used to determine the grey relation coefficient.

Using the value of the grey relation coefficient and introducing a weighting factor for all three linguistic variables, the degree of grey relation of each event can be calculated. This degree represents the ranking order of each event identified in the FMEA.

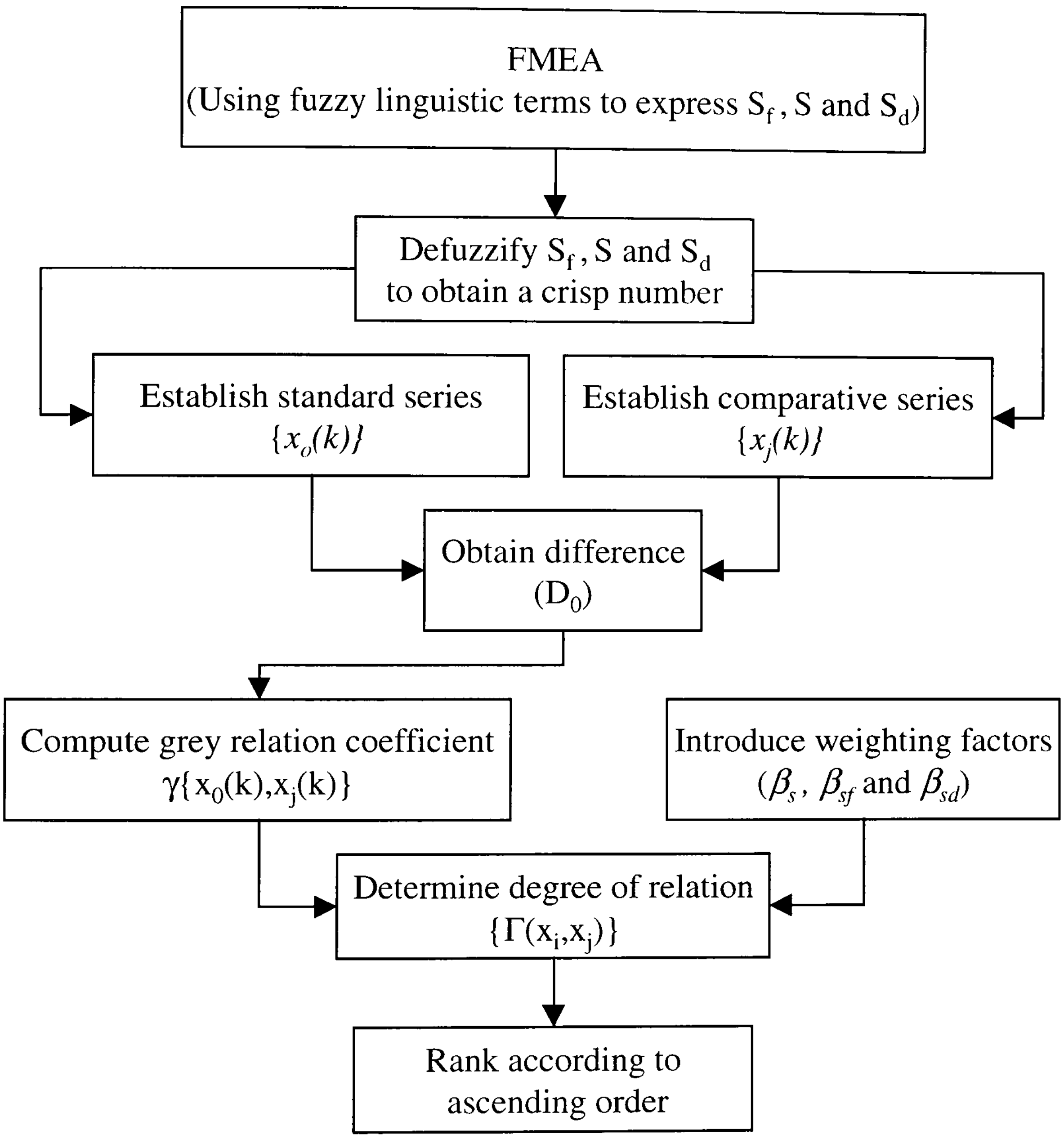

Figure 6.4 Flowchart of proposed grey theory approach.

Chen and Klien have proposed an easy defuzzification method for obtaining the crisp number of a fuzzy set as shown here in equation (9) [Chan C.B. and Klien C.M., 1997].

$$K(x) = \frac{\sum_{i=0}^{n}(b_i - c)}{\sum_{i=0}^{n}(b_i - c) - \sum_{i=0}^{n}(a_i - d)} \qquad (9)$$

where *K(x)* is the defuzzified crisp number. As an example, consider the defuzzification of the linguistic term *Moderate* as seen in figure 6.5. This linguistic term can be defuzzified to produce a crisp value as seen below.

$$K(x) = \frac{[b_0 - c] + [b_1 - c]}{\{[b_0 - c] + [b_1 - c]\} - \{[a_0 - d] + [a_1 - d]\}}$$

$$= \frac{[8-0]+[6-0]}{\{[8-0]+[6-0]\} - \{[4-10]+[6-10]\}} = 0.583$$

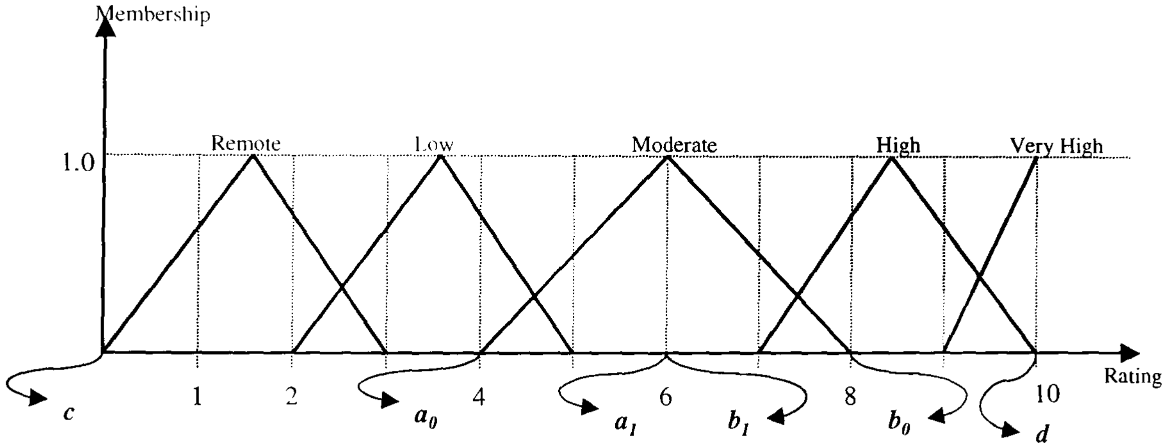

Figure 6.5 Defuzzification of the linguistic term *Moderate*

The values of c and d will remain the same for the defuzzification of all linguistic terms. The values a_0 and b_0 are rating values at the extreme limits of each linguistic term where the membership function is 0 and a_1 and b_1 are the rating values when the membership function is 1 (for a triangular membership function).

6.5.1 Comparative series

An informative series with n components or decision factors can be expressed as $x'_i = (x'_i(1), x'_i(2), \ldots x'_i(k)) \in X$, where $x_i(k)$ denotes the k^{th} factors of x_i. If all information series are comparable, the n information series can be described for the three linguistic variables as the following matrix [Deng J., 1989]:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{bmatrix} = \begin{bmatrix} x_1(1) & x_1(2) & x_1(3) \\ x_2(1) & x_2(2) & x_2(3) \\ . & . & . \\ . & . & . \\ x_n(1) & x_n(2) & x_n(3) \end{bmatrix}$$

For the application of this matrix in an FMEA study, the value of $x_i(k)$ represent the defuzzified crisp number describing each linguistic variable considered for the identified failure modes. For example, consider three failure events, A, B and C, where the linguistic terms have been assigned for the three variables considered as seen in table 6.5 and assume that the values in brackets represent the defuzzified value for the associated linguistic term. The information in table 6.5 can be represented in a matrix form to reflect the comparative series as seen below:

Failure events	***Probability of occurrence***	***Severity***	***Detectability***
A	*Remote* (0.196)	*Remote* (0.196)	*High* (0.370)
B	*Moderate* (0.583)	*Very High* (0.952)	*Low* (0.804)
C	*Remote* (0.196)	*Low* (0.370)	*Remote* (0.952)

Table 6.5 Example of comparative series

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} \text{Remote} & \text{Remote} & \text{High} \\ \text{Moderate} & \text{Very High} & \text{Low} \\ \text{Remote} & \text{Low} & \text{Remote} \end{bmatrix} = \begin{bmatrix} 0.196 & 0.196 & 0.370 \\ 0.583 & 0.952 & 0.804 \\ 0.196 & 0.370 & 0.952 \end{bmatrix}$$

6.5.2 Standard series

The standard series for the decision factors are generated by determining the optimal level of all factors for the events in the FMEA. From a safety point of view, the lowest level of all the factors are desired. Hence, the standard series $x_0 = [x_0(1), x_0(2),...x_0(k)]$ = [*Remote, Remote,.....Remote*]. This information is represented in the same way as the comparative series, in a matrix form. The standard matrix for the example shown in table 6.5 can be represented as seen below:

$$\begin{bmatrix} A_0 \\ B_0 \\ C_0 \end{bmatrix} = \begin{bmatrix} \text{Remote} & \text{Remote} & \text{Very High} \\ \text{Remote} & \text{Remote} & \text{Very High} \\ \text{Remote} & \text{Remote} & \text{Very High} \end{bmatrix} = \begin{bmatrix} 0.196 & 0.196 & 0.196 \\ 0.196 & 0.196 & 0.196 \\ 0.196 & 0.196 & 0.196 \end{bmatrix}$$

6.5.3 Difference

The difference between the comparative and standard series, D_0, is calculated and reflected in a form of a matrix as seen below:

$$D_0 = \begin{bmatrix} \Delta_{01}(1) & \Delta_{01}(2) & \Delta_{01}(3) \\ . & . & . \\ \Delta_m(1) & . & \Delta_m(3) \end{bmatrix}$$

where $\Delta_{0j}(k) = \| x_0(k) - x_i(k) \|$ and $x_0\ (k)$ is the standard series and $x_i\ (k)$ is the comparative series. For the example used in table 6.5, the difference of the comparative and standard series can be calculated as seen below:

$$D_0 = \begin{bmatrix} \|0.196-0.196\| & \|0.196-0.196\| & \|0.196-0.370\| \\ \|0.196-0.583\| & \|0.196-0.952\| & \|0.196-0.804\| \\ \|0.196-0.196\| & \|0.196-0.370\| & \|0.196-0.952\| \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0.174 \\ 0.387 & 0.756 & 0.608 \\ 0 & 0.174 & 0.756 \end{bmatrix}$$

6.5.4 Grey relation coefficient

The grey relation coefficient, $\gamma\{x_0(k),x_i(k)\}$, is calculated using equation (3) for each of the failure events identified in the FMEA. In the example used in table 6.5, the grey relation coefficient can be calculated as shown here, assuming that $\zeta = 0.5$:

Using,

$$\gamma(x_0(k),x_i(k)) = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \zeta \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \zeta \max_i \max_k |x_0(k) - x_i(k)|}$$

for event A, the grey relation coefficient for the probability of occurrence, γ_f, is given as:

$$\gamma_f = \frac{0 + [(0.5)(0.756)]}{0 + [(0.5)(0.756)]} = 1.000$$

Similarly, the grey relation for the other two linguistic variables (Severity (γ_s) and Detectability (γ_d)), can be calculated as follows:

$$\gamma_s = \frac{0 + [(0.5)(0.756)]}{0 + [(0.5)(0.756)]} = 1.000$$

$$\gamma_d = \frac{0 + [(0.5)(0.756)]}{0.174 + [(0.5)(0.756)]} = 0.684$$

The grey relation coefficient for events B and C is calculated in the same way. The results of these calculations are summarised as seen in table 6.6.

Failure event	γ_f	γ_s	γ_d
A	1	1	0.684
B	0.494	0.333	0.383
C	1	0.684	0.333

Table 6.6 Example of grey relation coefficient

6.5.5 Grey relation

6.5.5 Grey relation

The next step is to decide upon the weighting coefficient to obtain the degree of grey relation. Depending on the objective of the analysis and the reliability of the data available, the weighting coefficient (β_k), for the linguistic variables, S_f, S and S_d is to be determined. The weighting coefficient will have a large influence on the final ranking of the failure events. As such, it must be carefully selected and agreed upon by all experts involved in the study.

The degree of grey relation is calculated using equation (5) for each failure event incorporating the weighted variables. For example, assume that the value of β_f, β_s and β_d are 0.4, 0.4 and 0.2 respectively, the degree of grey relation in the example shown in table 6.5 can be calculated as seen here:

Using,

$$\Gamma(x_i, x_j) = \sum_{k=1}^{n} \beta_k \gamma\{x_i(k), x_j(k)\}$$

The grey relation for event A can be calculated as:

$$\Gamma_A = \{[(0.4)(1)] + [(0.4)(1)] + [(0.2)(0.684)]\} = 0.9368$$

The degree of grey relation for events B and C is calculated in the same way. The results of these calculations are summarised as seen in table 6.7.

Failure Events	Degree of grey relation
A	0.9368
B	0.4074
C	0.7402

Table 6.7 Example of degree of grey relation

CHAPTER 1

INTRODUCTION

Summary

This chapter briefly reviews the historical development of safety and reliability assessment within the maritime industry and outlines the application of such assessments. This is followed by a review of the historical development of safety and reliability assessment in the United Kingdom. The different databases that are available in the maritime industry are described, highlighting the information that each of these databases carry. A description of the proposed research is presented, followed by a summary of the work carried out in the research project.

1.1 Introduction

Safety was not considered to be a matter of public concern in ancient times, when accidents were regarded as inevitable or as the will of the gods. Modern notions of safety developed only in the 19th century as an outgrowth of the industrial revolution, when a terrible toll of factory accidents aroused humanitarian concern for their prevention. Today the concern for safety is worldwide and is the province of numerous governmental and private agencies at the local, national, and international levels.

The frequency and severity rates of accidents vary from country to country and from industry to industry. A number of accidents in the chemical, oil and gas, marine and nuclear industries over the years have increased the public and political pressure to improve the safety which protects people and environment. In the evolution of the approach to safety, there has been an increasing move towards risk management in conjunction with more technical solutions. Hazardous industries have developed approaches for dealing with safety and loss prevention, from design standards to plant

The identified failure events in the FMEA are ranked according to the ascending order of the degree of relation. This entails that the failure mode with the smallest degree of grey relation gets the highest priority for attention. For the example in table 6.7, failure event B would be at the top of the list for priority for attention, this will be followed by events C and A. The summary of the results for this example is shown in table 6.8.

Failure events	*Probability of occurrence*	*Severity*	*Detectability*	*Degree of grey relation*	*Ranking (priority for attention)*
A	*Remote*	*Remote*	*High*	0.9368	**3**
B	*Moderate*	*Very High*	*Low*	0.4074	**1**
C	*Remote*	*Low*	*Remote*	0.7402	**2**

Table 6.8 Example of ranking for failure events using the degree of grey relation

6.6 Application of the Proposed Approach to Fishing Vessels

The application of the fuzzy rule base and grey theory to FMEA is demonstrated for an ocean going fishing vessel. The FMEA in this example is limited to a few systems and not all failure modes are considered. The FMEA for fishing vessels investigates four different systems, that is, the structure, propulsion, electrical and auxiliary systems. Each of the systems is considered for different failure modes that could lead to an accident with undesired consequences. The effect of the failure mode at system and vessel level is studied along with the provisions that are in place/available to mitigate or reduce the risk. For each of the failure modes, the system is investigated for any alarms or condition monitoring arrangement, which are in place.

A traditional FMEA using the RPN ranking system is carried out in the first instance. This analysis is summarised in table 6.9. In this table, S_f represents the probability of occurrence, S represents the severity and S_d represents the detectability. The values for S_f, S and S_d are obtained by using the values detailed in tables 6.1, 6.2 and 6.3 respectively. The same pool of experts that carried out the analysis for the proposed approach is used for the traditional FMEA analysis. This ensures the consistency in the opinion of each expert.

Descrip.	*Comp.*	*Failure Mode*	*Failure effect (System)*	*Failure effect (Vessel)*	*Alarm*	*Provision*	S_f	S	S_d	*RPN*
Structure	Rudder bearing	Seizure	Rudder jam	No steering ctrl.	No	Stop vessel	1	8	3	24
Structure	Rudder Bearing	Breakage	Rudder loose	Reduced steering ctrl.	No	Stop vessel	1	8	3	24
Structure	Rudder structure	Structural failure	Function loss	Reduced steering	No	Use beams	2	8	4	64
Propulsion	Main Engine	Loss of output	Loss of thrust	Loss of speed	Yes	None	8	8	5	320
Propulsion	Main Engine	Auto shutdown	M/E stops	Loss of speed	Yes	Anchor	6	8	6	288
Propulsion	Shaft & propeller	Shaft breakage	Loss of thrust	Loss of speed	No	Anchor	2	8	1	16
Propulsion	Shaft & propeller	Shaft seizure	Loss of thrust	Loss of speed	Yes	Anchor	2	9	2	36
Propulsion	Shaft & propeller	Gearbox seizure	Loss of thrust	Loss of speed	Yes	Anchor	1	4	3	12
Propulsion	Shaft & propeller	Hydraulic failure	Cannot reduce thrust	Cannot reduce speed	No	Anchor	3	2	3	18
Propulsion	Shaft & propeller	Prop. blade failure	Loss of thrust	Loss of speed	No	Slow steaming	1	2	4	8
Air services	Air receiver	No start air press.	Cannot start M/E	No propulsion	Yes	Recharge receiver	4	2	3	24
Electrical Sys.	Power genera-tion	Generator fail	No elec.power	Some system failures	Yes	Use st-by generators	9	3	7	189
Electrical Sys.	Main switch board	Complete loss	Loss of main supply	No battery charging	Yes	Use emergency 24v	8	3	6	144
Electrical Sys.	Emer. S/B	Complete loss	Loss of emer.supp.	No emergency supp.	No	Use normal supply	3	7	4	84
Electrical Sys.	Main batteries	Loss of output	Loss of main 24v	Loss of main low volt.	Yes	Use emergency 24v	3	3	4	36
Electrical Sys.	Emer. batteries	Loss of output	Loss of emer.supp.	No emer.supp.	No	Use normal supply	1	8	3	24
Auxiliary Sys.	Fuel System	Contamina-tion	M/E and Gen stop	Vessels stops	Yes	Anchor	4	8	5	160
Auxiliary Sys.	Fuel system	No fuel to M/E	M/E stops	Vessel stops	No	Anchor	2	7	7	98
Auxiliary Sys.	Water system	No cooling water	Engine overheat	M/E auto cut-out	Yes	Use st-by pump	7	2	4	56
Auxiliary Sys.	Hydraulic	System loss	No hydraulics	No steering	Yes	Stop vessel	9	8	9	648
Auxiliary Sys.	Lube oil system	Loss of pressure	Low pressure cut-off	M/E stops	Yes	Use st-by pump	9	3	6	162

Table 6.9 Traditional FMEA for a fishing vessel

6.6.1 Fuzzy rule base application

The fuzzy rule base is developed in such a way so as to enable comparison with the traditional FMEA method. Hence, in fuzzy terms, the linguistic variables are determined to be the probability of occurrence, severity and detectability. Each of these variables can be described in linguistic terms as: *Remote, Low, Moderate, High* and *Very High*. The interpretations of these linguistic terms are given in table 6.4.

The membership functions of the five linguistic terms are as shown in figure 6.6. The linguistic terms for detectability will be in reverse order but with the same membership function. The triangular membership function is chosen so as to ensure a smooth transition from one linguistic term to the other. This is in parallel with the ability of the experts to represent certain sets of data in this fashion. Apart from that, the triangular membership function facilitates easy defuzzification of each linguistic term. The membership function for each linguistic term is evaluated for its limits on an arbitrary scale from 0 to 1.

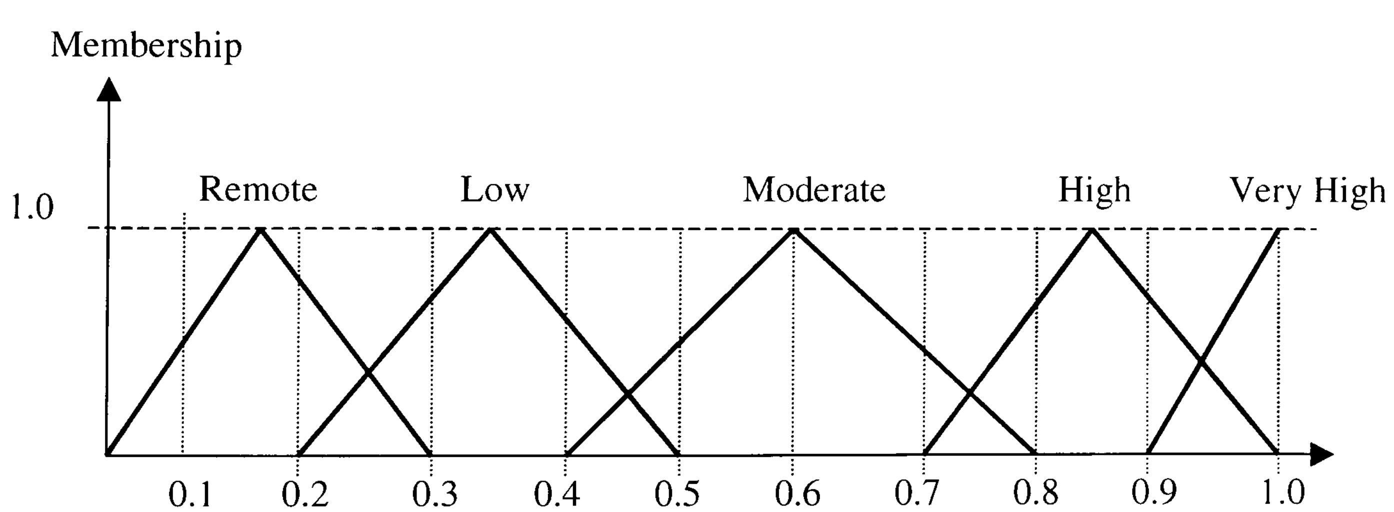

Figure 6.6 Membership function for the linguistic terms (generated by the experts)

The experts for this study were carefully selected to ensure a well-balanced fuzzy rule base. The expertise and knowledge of the five experts selected along with the degree of competency, C_i, are tabulated in table 6.10. The degree of competency assigned to the experts do not reflect their personal competency in their respective field, but instead it represents their knowledge and experience in dealing with safety assessments of fishing vessels and the fishing industry. The degree of competency, for each of the experts were decided and agreed upon by all the experts.

Expert	***Expertise and knowledge***	C_I
Expert 1	Safety analyst (marine & offshore).	0.3
Expert 2	Marine surveyor (fishing vessels).	0.3
Expert 3	Superintendent engineer (fishing vessels).	0.2
Expert 4	Marine operations engineer (merchant vessels).	0.1
Expert 5	Statistician.	0.1

Table 6.10 Selected experts and assigned degree of competency

The proposed approach introduces a linguistic variable called the *"priority for attention"* as the output of the FMEA, which can be linguistically expressed by five terms. These five linguistic terms describing the *priority for attention* are *Low, Fairly low, Moderate, Fairly high* and *High.*

The selected experts were asked to assign linguistic terms describing the *priority for attention* for different combinations of the linguistic terms describing the three linguistic variables (probability of occurrence, severity and detectability). Upon receiving the feedback from each of the experts and applying equation (7) with the values from table 6.10, the membership function for the linguistic variable *priority for attention* is determined and graphically represented in figure 6.7. Although the membership function for the *priority for attention* is triangular in shape, it can be noted that the membership functions for the linguistic terms are not symmetrical. This is due to the difference in opinions of individual experts. However, the graph still provides a smooth transition between states.

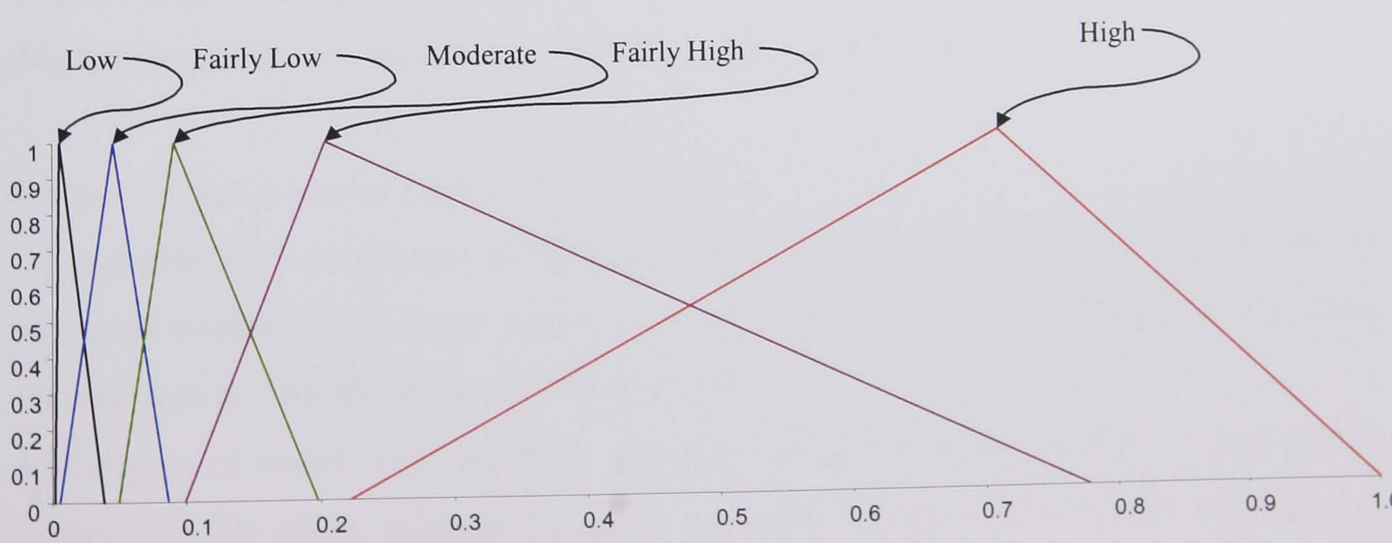

Figure 6.7 Membership function for the *priority for attention*

The support value for each of these linguistic terms is determined by taking the weighted average of the support values given by each expert. Using the information presented in figure 6.7, the support value is assumed to be represented on the x-axis when the membership function for the particular linguistic term reaches 1. Hence, the support values for the linguistic terms describing the *priority for attention* can be summarised as:

Fairly Low - 0.055

Low - 0.461

Moderate - 0.911

Fairly High - 2.041

High - 7.111.

The fuzzy rule base is generated based on the membership function derived from the experts (figures 6.6 and 6.7). A total of 125 rules are generated. However, these rules are combined (where possible) and the total number of rules in the fuzzy rule base is reduced to 35 rules. For example, consider these three rules:

Rule 1: if probability of occurrence is *Moderate,* severity is *Low* and detectability is *Low* then priority for attention is 0.66 *Moderate*, 0.94 *Fairly High.*
Rule 2: if probability of occurrence is *Low,* severity is *Moderate* and detectability is *Low* then priority for attention is 0.66 *Moderate*, 0.94 *Fairly High*
Rule 3: if probability of occurrence is *Moderate,* severity is *High* and detectability is *High*, then priority for attention is 0.66 *Moderate*, 0.94 *Fairly High*

Rules 1, 2, and 3 can be combined to read:
"if probability of occurrence is *Moderate,* severity is *Low* and detectability is *Low* or any combination of the three linguistic terms assigned to these variables, then priority for attention is 0.66 *Moderate*, 0.94 *Fairly High*".
The degree of belief 0.66 and 0.94, depends heavily upon the opinion of the experts involved in the study, as such, it can be assumed that these figures only represent an average value for all the opinions of the experts.

This method of rule reduction assumes that the probability of occurrence, severity and detectability have the same importance. Using this method to reduce the number of rules in the fuzzy rule base, a final set of rules is generated as shown in table 6.11.

Rule No	*Probability of occurrence*	*Severity*	*Detectability*	*Priority for attention*
1	Rem	Rem	V.High to High	Low
2	Rem	Rem	Mod	Low, 0.06 F.Low
3	Rem	Rem	Low	0.86 Low, 0.14 F.Low
4	Rem	Rem	Rem	0.78 Low, 0.2 F.Low
5	Low	Rem	High	Low, 0.16 F.Low
6	Low	Rem	Mod	0.86 Low, 0.48 F.Low
7	Low	Rem	Low	0.58 Low, 0.68 F.Low
8	Mod	Rem	Mod	0.5 Low, 0.92 F.Low
9	Mod	Rem	Low	0.8 F.Low, 0.4 Mod
10	Mod	Rem	Rem	0.92 F.Low, 0.8 Mod
11	High	Rem	Mod	0.74 F.Low, 0.4 Mod
12	High	Rem	Low	0.48 F.Low, 0.92 Mod
13	High	Rem	Rem	0.88 Mod, 0.1 F.High
14	V.High	Rem	High	0.48 Low, 0.88 F.Low
15	V.High	Rem	Rem	0.82 Mod, 0.36 F.High
16	Low	Low	High	0.86 Low, 0.78 F.Low
17	Low	Low	Mod	0.4 F.Low, 0.58 Mod
18	Low	Low	Low	0.8 F. Low, 0.92 Mod
19	Low	Low	Rem	0.92 F.Low, 0.7 Mod
20	Mod	Low	Mod	0.94 F.Low, 0.46 Mod
21	Mod	Low	Low	0.66 Mod,0.94 F.High
22	Mod	Low	Rem	0.92 Mod, 0.92 F.High
23	High	Low	Low	0.58 Mod,0.88 F.High
24	High	Low	Rem	0.72 F.High, 0.22 High
25	V.High	Low	Rem	0.98 F.High. 0.38 High
26	Mod	Mod	Mod	0.92 Mod,0.84 F.High
27	Mod	Mod	Low	0.4 Mod,0.66 F.High
28	Mod	Mod	Rem	0.94 F.High,0.56 High
29	High	Mod	Low	0.88 F.High,0.62 High
30	High	Mod	Rem	0.74 F.High,0.9 High
31	V.High	Mod	Rem	0.58 F.High,0.6 High
32	High	High	Low	0.52 F.High.0.98 High
33	High	High	Rem	0.3 F.High.0.42 High
34	V.High	High	Rem	High
35	V.High	V.High	Rem	High

Table 6.11 Reduced rules for the fuzzy rule base

Using the same data from the traditional FMEA, and expressing the three variables considered linguistically with the aid of the membership function in figure 6.6 and the fuzzy rule base in table 6.11, gives the results of the modified FMEA. These results are then defuzzified using the WMoM method as explained in section 6.4.3 to obtain a ranking as shown in table 6.12.

Descript.	*Component*	*Failure Mode*	S_f	*S*	S_d	*Priority for attention*	*Defuzzified ranking*
Structure	Rudder bearing	Seizure	Rem	High	High	0.58 Low,0.68 F.Low	0.274
Structure	Rudder Bearing	Breakage	Rem	High	High	0.58 Low,0.68 F.Low	0.274
Structure	Rudder structure	Structural failure	Rem	High	High	0.58 Low,0.68 F.Low	0.274
Propulsion	Main Engine	Loss of output	High	High	Mod	0.88 F. High, 0.62 High	4.136
Propulsion	Main Engine	Auto shutdown	Mod	High	Mod	0.4 Mod, 0.66 F.High	1.614
Propulsion	Shaft & propeller	Shaft breakage	Rem	High	V.High	0.86 Low, 0.14 F.Low	0.112
Propulsion	Shaft & propeller	Shaft seizure	Rem	High	V.High	0.86 Low, 0.14 F.Low	0.112
Propulsion	Shaft & propeller	Gearbox seizure	Rem	Low	High	Low,0.16 F.Low	0.111
Propulsion	Shaft & propeller	Hydraulic failure	Low	Rem	High	Low,0.16 F.Low	0.111
Propulsion	Shaft & propeller	Prop. Blade failure	Rem	Low	V.high	Low	0.055
Air services	Air receiver	No start air press.	Low	Rem	High	Low,0.16 F.Low	0.111
Electrical sys.	Power generation	Generator fail	High	Low	Mod	0.66 Mod,0.94 F.High	1.575
Electrical sys.	Main switch board	Complete loss	High	Low	Mod	0.66 Mod,0.94 F.High	1.575
Electrical sys.	Emergency S/B	Complete loss	Low	Mod	High	0.4 F.Low, 0.58 Mod	0.727
Electrical sys.	Main batteries	Loss of output	Low	Low	High	0.86 Low, 0.78 F.Low	0.248
Electrical sys.	Emergency batteries	Loss of output	Rem	High	High	0.58 Low,0.68 F.Low	0.274
Auxiliary sys.	Fuel sys.	Contamination	Low	High	Mod	0.66 Mod,0.94 F.High	1.575
Auxiliary sys.	Fuel sys.	No fuel to M/E	Rem	Mod	Mod	0.5 Low,0.92 F.Low	0.318
Auxiliary sys.	Water sys.	No cooling water	Mod	Low	High	0.4 F.Low, 0.58 Mod	0.727
Auxiliary sys.	Hydraulic	Sys. loss	High	High	Low	0.52 F.High,0.98 High	5.353
Auxiliary sys.	Lube oil sys.	Loss of pressure	High	Low	Mod	0.66 Mod, 0.94 F.High	1.575

Table 6.12 Modified FMEA using fuzzy rule base

From table 6.12, consider the first event (component-rudder bearing and failure mode-seizure), the three variables are linguistically described as:

Probability of occurrence (S_f) = *Remote*

Severity (S) = *High*

Detectability (S_d) = *High*

Using the fuzzy rule base generated in table 6.11, *Rule 7* will apply to the first event. This rule is interpreted to read as, "if the probability of occurrence is *Remote*, severity is *High* and detectability is *High*, then priority for attention is *0.58 Low, 0.68 Fairly low*". The conclusion *0.58 Low, 0.68 Fairly low* can be defuzzified using the WMoM method to produce a crisp number as shown here:

$$Z = \frac{(0.58 \times 0.055) + (0.68 \times 0.461)}{(0.58 + 0.68)}$$
$$= 0.274$$

where the support value for *Low* is 0.055 and *Fairly low* is 0.461 (as determined earlier). The priority for attention for the first event can be represented numerically by ***0.274.*** Similarly, all other events are analysed and the corresponding priorities for attention are obtained such that the higher the value of the defuzzified results, the higher the priority in the ranking series. From the analysis and the results presented in table 6.12, the failure event with the highest priority is failure component - hydraulic, failure mode - system loss, with a defuzzified result of 5.353. The lowest in the series is identified to be failure component - shaft & propeller, failure mode - propeller blade failure, with a defuzzified result of 0.055.

6.6.2 Grey theory application

There are many similarities in the data required to carry out the FMEA using grey theory, as it is to analyse it using a fuzzy rule base. Hence, the linguistic terms and membership functions generated for the fuzzy rule base application can be used in the grey theory method. The three variables are identical, these are the probability of occurrence (S_f), severity (S), and detectability (S_d). These three variables are described linguistically as *Remote, Low, Moderate, High* and *Very High*. The meaning of each of these terms are tabulated in table 6.4 and graphically represented in figure 6.6. These linguistic terms are defuzzified using equation (9) to produce a crisp number. The result of the defuzzification is tabulated as seen in table 6.13.

Linguistic Term	Defuzzified crisp number
Remote	0.196
Low	0.370
Moderate	0.583
High	0.804
Very High	0.952

Table 6.13 Defuzzified crisp number for linguistic terms describing the variables

The data from the FMEA in tables 6.9 and 6.12 is used here to demonstrate the application of the grey theory method. The same data is used for all three methods (traditional FMEA, fuzzy rule base and grey theory method), to enable comparisons of the results. The comparative series is generated based on the linguistic terms assigned to each event for the three variables considered and is represented in a matrix linguistically and then converted by defuzzification to express it numerically as seen in the matrix below.

$$x_i = \begin{bmatrix} \text{Rem} & \text{High} & \text{High} \\ \text{Rem} & \text{High} & \text{High} \\ \text{Rem} & \text{High} & \text{High} \\ \text{High} & \text{High} & \text{Mod} \\ \text{Mod} & \text{High} & \text{Mod} \\ \text{Rem} & \text{High} & \text{V.High} \\ \text{Rem} & \text{High} & \text{V.High} \\ \text{Rem} & \text{Low} & \text{High} \\ \text{Low} & \text{Rem} & \text{High} \\ \text{Rem} & \text{Low} & \text{V.High} \\ \text{Low} & \text{Rem} & \text{High} \\ \text{High} & \text{Low} & \text{Mod} \\ \text{High} & \text{Low} & \text{Mod} \\ \text{Low} & \text{Mod} & \text{High} \\ \text{Low} & \text{Low} & \text{High} \\ \text{Rem} & \text{High} & \text{High} \\ \text{Low} & \text{High} & \text{Mod} \\ \text{Rem} & \text{Mod} & \text{Mod} \\ \text{Mod} & \text{Low} & \text{High} \\ \text{High} & \text{High} & \text{Low} \\ \text{High} & \text{Low} & \text{Mod} \end{bmatrix} = \begin{bmatrix} 0.196 & 0.804 & 0.370 \\ 0.196 & 0.804 & 0.370 \\ 0.196 & 0.804 & 0.370 \\ 0.804 & 0.804 & 0.583 \\ 0.583 & 0.804 & 0.583 \\ 0.196 & 0.804 & 0.196 \\ 0.196 & 0.804 & 0.196 \\ 0.196 & 0.370 & 0.370 \\ 0.370 & 0.196 & 0.370 \\ 0.196 & 0.370 & 0.196 \\ 0.370 & 0.196 & 0.370 \\ 0.804 & 0.370 & 0.583 \\ 0.804 & 0.370 & 0.583 \\ 0.370 & 0.583 & 0.370 \\ 0.370 & 0.370 & 0.370 \\ 0.196 & 0.804 & 0.370 \\ 0.370 & 0.804 & 0.583 \\ 0.196 & 0.583 & 0.583 \\ 0.583 & 0.370 & 0.370 \\ 0.804 & 0.804 & 0.804 \\ 0.804 & 0.370 & 0.583 \end{bmatrix}$$

The standard series is taken to be the lowest level of the linguistic term describing all three variables, which is *Remote* for the Probability and severity and *Very High* for the detectability. When the linguistic term *Remote* is defuzzified, the crisp number obtained is 0.196, this represents the average value, as such the value 0 (lowest possible value) is used to represent the linguistic term *Remote* in the standard series. A matrix representing the standard series is generated as shown below.

$$x_0 = \begin{bmatrix} \text{Rem} & \text{Rem} & \text{V.High} \\ \text{Rem} & \text{Rem} & \text{V.High} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The difference between the comparative and standard series, D_0, is then calculated and expressed as a matrix. Since all entries for the matrix representing the standard series was determined to be 0, the difference between the comparative and standard series would be equal to the comparative series (considering that $\Delta_{0j}(k) = \| x_0(k) - x_i(k) \|$).

Using the values obtained from the difference of the standard and comparative series, the grey relation coefficient, $\gamma\{x_0(k), x_i(k)\}$, is calculated using equation (3) for each variable of the events identified in the FMEA. Equation (3) can be simplified and is represented by equation (10):

inspections and technical safety, through to safety auditing and human factors [Trbojevic V.M. and Soares C.G., 2000].

As far as the marine industry is concerned, tragic accidents such as the *Herald of Free Enterprise* and *Derbyshire*, together with environmental disasters such as *Exxon Valdez* and *Amoco Cadiz,* have focused world opinion on ship safety and operation. This demand for improved safety requires comprehensive safety analyses to be developed in order to identify ways to improve human and ship reliability. These improved safety prediction models will ensure efficient, economic and safe ship operation.

1.2 Safety and Reliability Development in the Maritime Industry

Reliability and safety methods saw a rapid development after the Second World War. These methods were mainly concerned with military use for electronics and rocketry studies. The first predictive reliability models appeared in Germany on the V1 missile project where a reliability level was successfully defined from reliability requirements and experimentally verified on components during their development stages [Bazovsky I., 1961].

The first formal approach to shipboard reliability was the Buships specification, MIL-R-22732 of July 31, 1960 prepared by the United States of America's Department of Defence and dealt with ground and shipboard electronic equipment [MIL, 1960]. Subsequently in 1961 the Bureau of Weapons issued MIL standards concerning reliability models for avionics equipment and procedures for the prediction and reporting of the reliability of weapon systems. This was due to the fact that the growing complexities of electronic systems were responsible for the failure rates leading to a significantly reduced availability on demand of the equipment.

In February 1963 the first symposium on advanced marine engineering concepts for increased reliability was held at the office of Naval Research at the University of Michigan. In December 1963 a paper entitled "Reliability engineering applied to the marine industry" [Harrington R.L. and Riddick R.P., 1963] was presented at the Society

$$\gamma(x_o(k), x_i(k)) = \frac{\Delta_{\min} - \zeta\Delta_{\max}}{\Delta_{0j}(k) - \zeta\Delta_{\max}} \qquad (10)$$

where

$\Delta_{\min} = 0.196$

$\Delta_{\max} = 0.804$

$\zeta = 0.5$

ζ is an identifier, $\zeta \in (0,1)$, only affecting the relative value of risk without changing the priority. Generally, ζ can be set to 0.5 [Deng J., 1989].

One of the objectives of applying an FMEA study to fishing vessels is to identify areas where safety features are lacking in the system. These include interlocks, alarms, auto cut-off/shut-down, condition monitoring and redundancy features. Due to the organisational and operating nature of fishing vessels, incorporating/improving safety features may be the easiest and most effective way to improve the operational safety of the vessel. As such the weighting coefficient (β_k), for the decision factors, S_f, S and S_d should be such that $\beta_{Sd} > \beta_S > \beta_{Sf}$. This would entail giving more preference to the detectability factor in the analysis. Hence, The weighting coefficient (β_k), is set to be 0.2, 0.3 and 0.5 for the probability of occurrence, severity and detectability respectively. Using these values, the degree of grey relation is calculated using equation (5).

Consider the first event where S_f, S and S_d are assigned *Remote, High* and *High* for the probability of occurrence, severity and detectability respectively. The grey relation coefficient γ_f, γ_s and γ_d is calculated as shown here:

$$\gamma_f = \frac{0.196 + [(0.5)(0.804)]}{0.196 + [(0.5)(0.804)]} = 1$$

$$\gamma_s = \frac{0.196 + [(0.5)(0.804)]}{0.804 + [(0.5)(0.804)]} = 0.496$$

$$\gamma_d = \frac{0.196 + [(0.5)(0.804)]}{0.370 + [(0.5)(0.804)]} = 0.775$$

Substituting these values and the weighting coefficient into equation (5) will give the degree of relation for the first event as seen here:

$$\Gamma(x_i, x_j) = \{[(0.2)(1)] + [(0.3)(0.496)] + [(0.5)(0.775)]\} = 0.736$$

Similarly, the degree of relation is calculated for all the events identified in the FMEA to produce a ranking that determines the priority for attention. The complete analysis of the test case using grey theory is tabulated as seen in table 6.14.

Description	Component	Failure Mode	S_f	γ_f	S	γ_s	S_d	γ_d	Grey Relation
Structure	Rudder bearing	Seizure	Rem	1.000	High	0.496	High	0.775	0.736
Structure	Rudder bearing	Breakage	Rem	1.000	High	0.496	High	0.775	0.736
Structure	Rudder structure	Structural failure	Rem	1.000	High	0.496	High	0.775	0.736
Propulsion	Main Engine	Loss of output	High	0.496	High	0.496	Mod	0.607	0.552
Propulsion	Main Engine	Auto shutdown	Mod	0.607	High	0.496	Mod	0.607	0.574
Propulsion	Shaft & propeller	Shaft breakage	Rem	1.000	High	0.496	V.High	1.000	0.849
Propulsion	Shaft & propeller	Shaft seizure	Rem	1.000	High	0.496	V.High	1.000	0.849
Propulsion	Shaft & propeller	Gearbox seizure	Rem	1.000	Low	0.775	High	0.775	0.820
Propulsion	Shaft & propeller	Hydraulic failure	Low	0.775	Rem	1.000	High	0.775	0.843
Propulsion	Shaft & propeller	Prop. blade failure	Rem	1.000	Low	0.775	V.high	1.000	0.933
Air services	Air receiver	No start air press.	Low	0.775	Rem	1.000	High	0.775	0.843
Electrical Systems	Power generation	Generator fail	High	0.496	Low	0.775	Mod	0.607	0.635
Electrical Systems	Main switch board	Complete loss	High	0.496	Low	0.775	Mod	0.607	0.635
Electrical Systems	Emergency S/B	Complete loss	Low	0.775	Mod	0.607	High	0.775	0.725
Electrical Systems	Main batteries	Loss of output	Low	0.775	Low	0.775	High	0.775	0.775
Electrical Systems	Emergency batteries	Loss of output	Rem	1.000	High	0.496	High	0.775	0.736
Auxiliary Systems	Fuel system	Contamination	Low	0.775	High	0.496	Mod	0.607	0.607
Auxiliary Systems	Fuel System	No fuel to M/E	Rem	1.000	Mod	0.607	Mod	0.607	0.686
Auxiliary Systems	Water system	No cooling water	Mod	0.607	Low	0.775	High	0.775	0.741
Auxiliary Systems	Hydraulic	Sys. Loss	High	0.496	High	0.496	Low	0.496	0.496
Auxiliary Systems	Lube oil system	Loss of pressure	High	0.496	Low	0.775	Mod	0.607	0.635

Table 6.14 Modified FMEA using grey theory

6.7 Analysis of Results

The results obtained for the FMEA using the proposed approach is collated with the results obtained from the traditional FMEA using the RPN method and is given in table 6.15. From this table, consider event 1 and 11, where the RPN is 24. From table 6.9, the values of S_f, S and S_d are 1, 8 and 3 for event 1 and 4, 2 and 3 for event 11, hence a RPN of 24 is obtained. Although the RPN for both events are the same, the risk levels are different. This difference is obvious when the fuzzy rule base method and grey theory is applied. The results of the proposed methods shows that event 1 has a higher priority compared to event 11. However, the traditional RPN method puts these two events as having the same priority.

ID	Component	Failure Mode	RPN	Fuzzy rule base	Grey Theory	Ranking (RPN)	Ranking (Rule base)	Ranking (Grey theory)
1	Rudder bearing	Seizure	24	0.274	0.736	15	11	10
2	Rudder Bearing	Breakage	32	0.274	0.736	14	11	10
3	Rudder structure	Structural failure	64	0.274	0.736	10	11	10
4	Main Engine	Loss of output	320	4.136	0.552	2	2	2
5	Main Engine	Auto shutdown	288	1.614	0.574	3	3	3
6	Shaft & propeller	Shaft breakage	16	0.112	0.849	19	16	19
7	Shaft & propeller	Shaft seizure	36	0.112	0.849	12	16	19
8	Shaft & propeller	Gearbox seizure	12	0.111	0.820	20	18	16
9	Shaft & propeller	Hydraulic failure	18	0.111	0.843	18	18	17
10	Shaft & propeller	Prop. blade fail	8	0.055	0.933	21	21	21
11	Air receiver	No start air press.	24	0.111	0.843	15	18	17
12	Power generation	Generator fail	189	1.575	0.635	4	4	5
13	Main switch board	Complete loss	144	1.575	0.635	7	4	5
14	Emer. S/B	Complete loss	84	0.727	0.725	9	8	9
15	Main batteries	Loss of output	36	0.248	0.775	12	15	15
16	Emer. batteries	Loss of output	24	0.274	0.736	15	11	10
17	Fuel System	Contamination	160	1.575	0.607	6	4	4
18	Fuel system	No fuel to M/E	98	0.318	0.686	8	10	8
19	Water system	No cooling water	56	0.727	0.741	11	8	14
20	Hydraulic	System loss	648	5.353	0.496	1	1	1
21	Lube oil system	Loss of pressure	162	1.575	0.635	5	4	5

Table 6.15 Ranking comparison

The ranking produced by the proposed methods do not differentiate events that have the same linguistic terms describing the factors considered. For example, events 1,2 and 3, where S_f, S and S_d are assigned *Remote, High* and *High* respectively, the defuzzified ranking is 0.274 and the degree of grey relation is 0.736 for all three events. This entails that these three events should be given the same priority for attention. The RPN method however, produces a result of 24, 32 and 64 for events 1, 2 and 3 respectively. This denotes that event 3 has the highest priority followed by event 2 and 3. This ranking could be misleading, especially when the safety data used for the analysis is accompanied with a high level of uncertainty.

The effects of the weighting coefficient introduced in the grey theory method can be clearly seen in the results obtained for events 17 and 21, where Sf, S and S_d are assigned *Low, High* and *Moderate* and *High, Low* and *Moderate* respectively. Using the fuzzy rule base to analyse these two events produces a defuzzified ranking of 1.575, however, when using the grey theory method (incorporating the weighted coefficient), the grey relation ranking is 0.607 and 0.635 for events 17 and 21 respectively. This entails that event 17 should be given a higher priority compared to event 21. This shows that a more accurate ranking can be achieved by the application of the fuzzy rule base and grey theory to FMEA.

6.8 Conclusion

When conducting an FMEA for safety assessment purposes, precision should not be forced where data is unreliable and scarce. Hence, to ask an analyst or an expert to assign scores ranging from 1 to 10 (as done in the RPN method) for the different factors considered would produce a false and unrealistic impression. The use of linguistic terms in the proposed approach allows for the experts to assign a more meaningful value for the factors considered. This ensures that identified events do not get overlooked (due to a low RPN) when considering the priority for attention.

The advantages of the proposed fuzzy rule base and grey theory approach for application to FMEA of fishing vessels can be summarised as follows:

- It can be used for systems where safety data is unavailable or unreliable, as it does not force precision.

- It provides an organised method to combine expert knowledge and experience for use in an FMEA study.
- The use of linguistic terms in the analysis enables the experts to express their judgements more realistically and hence improving the applicability of the FMEA.
- The flexibility of assigning weight to each factor in the FMEA provides a means of specifically identifying weak areas in the system/component studied.

The proposed approach using fuzzy rule base (without the weighting factors of the linguistic variables) could be suitable for use in step 1 of the FSA process (at the hazard-screening phase) as discussed in chapter 4 (section 4.2.1). During the hazard-screening phase, only a relative ranking order is needed. This will distinguish the hazards with a high-risk level from those with a low-risk level.

The proposed approach using grey theory (with the weighting factors of the linguistic variables) would be suitable for use in step 2 of the FSA (risk estimation phase) as discussed in chapter 2 (section 4.2.2). At this stage of the FSA, a more detailed analysis of each hazard is required to produce a ranking order that would determine the allocation of the limited resources. As the proposed method provides the analyst with the flexibility to decided which factor is more important to the analysis, the outcome of the analysis will provide valuable information for the decision making process.

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CHAPTER 7

MAINTENANCE MODELLING

Summary

The data analysis in chapter 2 showed that more than 50% of accidents on fishing vessels involved machinery failure. Upon investigation of several fishing vessels in the UK, it was found that maintenance activities on board these vessels were almost non-existent. A review of different maintenance concepts is carried out in the first instance followed by a summary of the advantages and disadvantages of these concepts. The current maintenance practice of fishing vessels is reviewed and a proposal is presented to reduce machinery failure on these vessels by means of implementing an inspection regime based on the delay-time concept. The proposed approach provides an alternative solution to the current maintenance practice to reduce cost incurred and downtime suffered by fishing vessels.

7.1 Introduction

Maintenance is defined as the combination of all technical and administrative actions, including supervision actions, intended to retain an entity in, or restore it to a state in which it can perform a required function. It involves planned and unplanned activities being carried out to ensure an acceptable state of operation. Selection of a maintenance strategy will depend on one or a combination of the following criteria: maximisation of reliability, minimisation of downtime and minimisation of total maintenance cost [Savic D.A. et. al., 1995].

The impact of the maintenance policy on total maintenance cost is hard to predict [Rischel T.D. and Christy D.P., 1996]. Any breakdown in machine operation results in disruption of production and leads to additional costs due to downtime, loss of

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of Naval Architects and Marine Engineers (SNAME) and in June the following year another paper, entitled "Reliability in shipbuilding" [Dunn T.W., 1964] was presented. Following the presentation of these two papers, SNAME in 1965 established Panel M-22 to investigate the new discipline as applied to marine machinery and make it of use to the commercial marine industry.

In the last two decades, stimulated by public reaction and health and safety legislation, the use of risk and reliability assessment methods has spread to the higher risk industries. The usage is now spreading to an even wider range of applications. The Reactor Safety Study undertaken by the U.S.A [U.S Nuclear Regulatory Commission, 1975] and the Canvey studies performed by the UK Health and Safety Executive [U.K. Health and Safety Executive, 1978, 1981a, 1981b] resulted from a desire to demonstrate safety to a doubtful public. Both these studies made considerable use of quantitative methods, for assessing the probability of failure and for determining consequence models.

1.3 Present Status in the United Kingdom

There is a long history in Great Britain of research, development and successful practical application of safety and reliability technology. There is a continuing programme of fundamental research in areas such as software reliability and human error in addition to further development of the general methodology available to the analyst. Much of the development work was carried out by the nuclear industry.

Based on the considerable expertise gained in the assessment of nuclear plants, a National Centre for System Reliability (NCSR) was established by the UK Atomic Energy Authority (UKAEA) to promote the use of reliability technology. This organisation plays a leading role in research, training, consultancy and data collection. The NCSR is part of the safety and reliability directorate of the UKAEA, which has played a major role in formulating legislation on major hazards, and has carried out major safety studies on industrial plants. It is noted that some of the major hazard studies commissioned at the national level in the UK have included the evaluation of the production, decrease in productivity and quality and inefficient use of personnel, equipment and facilities [Ashayeri J. et. al., 1996].

In the shipping industry, there are some specific problems with regards to maintenance, that need to be considered when developing a maintenance model. These include:

- The high degree of isolation from repair and spares facilities.
- The high cost of transport unit (i.e. the ship).
- The high cost of a ship out of service.
- Varying costs, availability and quality of labour and spares throughout the world.
- Shipboard personnel are operators as well as maintainers and with fishing vessels, they could be the owners as well.
- The frequency with which personnel join and leave ships, creating a need for continuity of ships maintenance plans.
- Severe safety and insurance conditions, necessitating rigorous survey requirements.

Several of these problems are undeniably important to the fishing industry as will be discussed in section 7.2.

7.1.1 Modern maintenance concepts

Reliability Centred Maintenance (RCM) sometimes referred to as Preventive Maintenance Optimisation (PMO) has become popular in recent years with several industries. The concept has been discussed and elaborated on by several authors [Worledge D.H., 1993; Rausand M., 1998; Sherwin D.J., 1999]. RCM is a procedure for determining maintenance strategies based on reliability techniques and encompasses well-known analysis methods such as Failure Mode, Effects and Criticality Analysis (FMECA). RCM procedure takes into account the prime objectives of a maintenance programme:

- Minimise costs.
- Meet safety and environmental goals.
- Meet operational goals.

The RCM process begins with a Failure Mode and Effects Analysis (FMEA), which identifies the critical plant failure modes in a systematic and structured manner. The process then requires the examination of each critical failure mode to determine the optimum maintenance policy to reduce the severity of each failure. The chosen maintenance strategy must take into account cost, safety, environmental and operational consequences. The effects of redundancy, spares costs, maintenance crew costs, equipment ageing and repair times must be taken into account along with many other parameters.

Classical RCM, as it was first developed, is expensive to implement since rigorous FMEA had to be developed. Classic RCM includes calculating probabilities of failure for each piece of equipment (reliability calculations for each system) and it takes teams of engineer's months/years to complete, and requires a lot of historical data. As such it consumes a lot of time.

The streamlined RCM approach however, recognises the value of the personnel along with their experience and takes advantage of their extensive experience running the facility. By talking to the personnel on site, the equipment can be categorised and the initial phase of a RCM program can be set up.

Streamlined RCM divides facility equipment into four major categories:

- Reactive Maintenance
- Preventive Maintenance
- Predictive Maintenance
- Proactive Maintenance

These four major categories summarise the available maintenance concepts in the industry. Each concept can be implemented as a stand-alone regime or it could be integrated with each other to produce a sound regime.

7.1.2 Reactive maintenance

Reactive maintenance is referred to by many different names, such as, breakdown maintenance, repair, fix-when-fail and run to failure maintenance. When applying this maintenance strategy, a piece of equipment receives maintenance (repair of replacement) only when the deterioration of the equipment's condition causes functional failure. The strategy of reactive maintenance assumes that failure is equally likely to occur in any part, component or system. Thus, this assumption precludes identifying a specific group of repair parts as being more necessary or desirable than others.

The major downside of reactive maintenance is unexpected and unscheduled equipment downtime. If the equipment fails and repair parts are not available, delays ensue while parts are ordered and delivered. When this is the sole type of maintenance practised, both labour and materials are used inefficiently. Labour resources are thrown at whatever breakdown is most pressing. A purely reactive maintenance programme ignores the many opportunities to influence equipment survivability. However, it can be effective if used selectively and performed as a conscious decision based on the results of an RCM analysis. Equipment that can be reactively maintained must be non-critical and will not pose any safety hazard or effect the operation of the system as a whole.

7.1.3 Preventive maintenance

In Preventive Maintenance (PM), maintenance activities are performed before equipment failure. PM involves the repair, replacement and maintenance of equipment in order to avoid unexpected failure during use. PM with inspection intervals is a commonly used maintenance strategy [Ben-Daya M. and Hariga M., 1998; Lofsten H., 1999; Crocker J., 1999]. The objective of any PM programme is to minimise the total cost of inspection, repair and also equipment downtime. Two approaches have evolved from performing PM [Mann L. et. al., 1999]. The traditional approach is based on the use of statistical and reliability analysis of equipment failure. The second approach involves the use of sensor-based monitoring of equipment condition in order to predict when a machine failure will occur. Under this condition-based PM, intervals between PM work are not fixed, but are carried out only "when needed".

Traditional PM is keyed to failure rates and times between failures. It assumes that these variables can be determined statistically, and that one can therefore replace a part that is "due for failure" shortly before it fails. The availability of statistical failure information tends to lead to fixed schedules for the overhaul of equipment or the replacement of parts subject to wear. PM is based on the assumption that the overhaul of equipment by disassembly and replacement of parts restores it to a "like-new" condition with no harmful side effects.

Failure rate or its reciprocal, Mean Time Between Failure (MTBF), is often used as a guide to establishing the interval at which the maintenance tasks should be carried out. The major weakness in using these measurements to establish task periodicity is that, failure rate data determines only the average failure rate. In reality, failures are equally likely to occur at random times and with a frequency unrelated to the average failure rate. There has been considerable progress in recent years in developing PM models for particular equipment addressing this problem [Hariga M., 1994; Srikrishna S. et. al., 1996; Luce S., 1999]. Other works include an attempt to model PM using Bayesian approach [Percy D.F. and Kobbacy K.A.H., 1996] and the reduction of PM cost error due to uncertainty [Cavalier M.P. and Knapp G.M., 1996].

In summary, PM can be costly and ineffective when it is the sole type of maintenance practised.

7.1.4 Predictive maintenance

Predictive maintenance or Condition Monitoring (CM), uses primarily non-intrusive testing techniques, visual inspections and performance data to assess equipment condition. It replaces arbitrarily timed maintenance tasks with maintenance scheduled only when warranted by equipment condition. Continuous analysis of equipment condition monitoring data allows planning and scheduling of maintenance or repairs in advance of catastrophic and functional failure.

The CM data collected is used in one of the following ways to determine the condition of the equipment and to identify the precursors of failure:

- *Trend analysis* - Reviewing data to see if the equipment is on an obvious and immediate "downward slide" toward failure [Newell G.E., 1999].

- *Pattern recognition* - Looking at the data and realising the casual relationship between certain events and equipment failure [Parrondo J.L. et. al., 1998].
- *Test against limits and ranges* - Setting alarm limits (based on professional intuition) and seeing if they are exceeded [Sherwin D.J. and Al-Najjar B., 1999].
- *Statistical process analysis* - If published failure data on a certain equipment/component exists, comparing failure data collected on site with the published data to verify/disapprove that the published data can be used for the system analysed.

CM does not lend itself for all types of equipment or possible failure modes and therefore should not be the sole type of maintenance practised.

7.1.5 Proactive maintenance

Proactive maintenance provides a logical culmination to the other types of maintenance described above. It improves maintenance through better design, installation, maintenance procedures, workmanship and scheduling.

Proactive maintenance is characterised by the following attributes:

- Maintaining a feedback loop from maintenance to design engineers, in an attempt to ensure that design mistakes made in the past are not repeated in future designs.
- Viewing maintenance and supporting functions from a life-cycle perspective. This perspective will often show that reducing maintenance activity to save money in the short term often costs more in the long term.
- Constantly re-evaluating established maintenance procedures in an effort to improve them and ensure that they are being applied in the proper mix.

Proactive maintenance uses the following basic techniques to extend machinery life:

- Proper installation and precision rebuild.
- Failed-part analysis.
- Root-cause failure analysis.
- Rebuild verification.
- Age exploration.
- Recurrence control.

The major difference in proactive maintenance compared to other maintenance programmes is that it doesn't just treat the symptom but determines the root cause of repeated failures and addresses them.

7.1.6 Summary of maintenance techniques

Each of the maintenance concepts reviewed in section 7.1 is associated with certain advantages and disadvantages. Hence, these concepts should be used in a right combination so as to ensure a sound and cost-effective maintenance regime. RCM attempts to integrate these techniques and its application has proven to be successful in the past [Goodfellow J.W., 2000; Fonseca D.J. and Knapp G.M., 2000; Hauge B.S. et. al., 2000]. Table 7.1 summarises the advantages and disadvantages of the described maintenance concepts.

Maintenance	*Advantages*	*Disadvantages*
Reactive	• Cost effective for small, non-critical equipment.	• Possible costly downtime. • Possible damage to associated equipment. • High cost for Medium/High priority equipment.
Preventive	• Provides first line of defence.	• Often wasteful. • Does not prevent certain failure. • Can introduce problems. • Requires large parts inventory.
Predictive	• Reduces inventory cost. • Reduces downtime. • Reduces damage to associated equipment. • Reduces unnecessary parts replacement.	• When implemented alone, does not address root causes of problems. • CM equipment are costly.
Proactive	• Addresses root causes of problems. • Reduces maintenance costs beyond predictive levels. • Extends equipment life.	• Cost.

Table 7.1 Advantages and disadvantages of maintenance concepts

7.2 Current Maintenance Practice on Fishing Vessels

The current maintenance practice on fishing vessels varies according to the operating policies of the owner/operator. On most occasions, the crew does not carry out regular maintenance while at sea. As such, all maintenance work is completed while the vessel is at the discharging port. The time between discharge ports can be as long as 3 to 6 months, which allows for failures on the machinery to propagate and lead to a catastrophic breakdown.

The voyage duration of the vessel depends solely on the success of the catch. Hence, the vessel will stay at the fishing grounds as long as it is possible to maximise the catch. Should the vessel suffer any breakdown during this period, the vessels' crew will attempt to carry out emergency repairs. The amount of repair and replacement of damaged equipment is very limited, mainly due to several reasons as seen here:

- Limited amount of spares carried on board the vessel.
- Limited number of tools available to carry out the repairs.
- The competency of the crew to carry out complicated repairs.
- Rough weather conditions (working on small vessels becomes difficult and dangerous).
- Available manpower on board the vessel may not be sufficient to carry out major repairs.

Due to these reasons, only temporary repairs are carried out to enable the vessel to steam to the closest port, where more permanent repairs can be carried out. However, if temporary repairs are not sufficient to enable the vessel to move to the closest port, either a shore team is called out to the ship or the ship is towed back to the closest port by tugboats. Both these options are very costly especially when the vessel is stranded in the middle of the ocean.

During the discharging period at port, equipment requiring maintenance will be attended to by personnel contracted by the ship owner. The time spent at port by the vessel will depend on the unloading time required. This could vary from a few days to a few weeks.

Hence, the time available to carry out repairs is limited. In order to enable the best utilisation of the available time, a repair list is prepared by the ships Chief Engineer while the vessel is at sea. This list is sent to the shore office (if one exists) to plan the maintenance activities at the next discharging. This list will be combined with a list created by the superintendent of the vessel - upon an inspection of the ship when it arrives at the discharging port. Large fishing vessel companies that have a structured organisational hierarchy adopt this method. Skipper owned vessels, will depend on their contacts ashore to arrange for the repairs to be expedited.

There are several routine maintenances that are carried out regularly on board fishing vessel. These include:

- Filter cleaning.
- Fishing net mending.
- Oil changing.
- General cleaning and lubricating of machinery.
- De-rusting and painting.

These activities can be summarised as the bare minimum requirement of an engineering system.

It has been observed that many fishing vessels call into a floating dock once a year to carry out a complete inspection/repair/overhaul of equipment on board. These repairs and overhauls are normally carried out by yard workers or specially contracted personnel. These vessels also come in for dry-docking every 3 to 5 years (depending on the condition of the vessel) to carry out repairs on seawater valves, replacement of hull anodes, inspection of propeller, tail shaft and rudder and any other fitting which lies beneath the water line.

Considering the current status of maintenance practice on fishing vessels and the high number of accidents caused by the lack of maintenance activities, it is suggested that a maintenance regime be introduced. This regime should be practical (considering the limitations associated with fishing vessels) and effective. Taking into account the ability and competency of crew on board fishing vessels, it is recommended that an inspection regime be implemented in the first instance. This can be followed by an implementation of other maintenance concepts in the future, together with appropriate training for the crew.

This chapter proposes a method to determine inspection intervals to complement regular maintenance planning. The purpose of inspection at intervals is to increase the up time of systems with comparatively high downtime costs. By regularly carrying out inspections on equipment, abnormalities can be identified and corrective action can be taken to prevent a catastrophic failure. However, carrying out regular inspection on a system that is continuously operating may result in higher operating cost due to downtime and the cost of inspection. A model using Delay Time Analysis (DTA) is proposed to estimate the expected downtime, cost and safety criticality for various inspection intervals. The optimal inspection period can be obtained depending upon the criteria chosen such that the downtime or cost be minimised or safety maximised.

7.3 Background of Delay-Time

The time to failure of equipment is a function of its maintenance concept, and to capture this interaction the conventional time to first failure of reliability theory requires enrichment. This may be achieved using the delay-time concept.

Considerable work has been carried out on the modelling of this concept to production plants [Christer A.H. and Walker W.M., 1984a; Christer A.H. et. al., 1995; Christer A.H. et. al., 1998]. Other works include the application to gearbox failure on busses [Leung F. and Kit-leung M., 1996], preventive maintenance modelling for a vehicle fleet [Christer A.H. and Walker W.M., 1984b] and application to concrete structures [Burley E. et. al., 1989; Redmond D.F. et. al., 1997].

Before a component breaks down (assuming it is not a sudden failure), there will be telltale signs of reduced performance or abnormalities. The time between the first identification of abnormalities (initial point) and the actual failure time (failure point) will vary depending on the deterioration rate of the component. This time period is called the delay time or opportunity window to carry out maintenance or an inspection. The delay time is illustrated by means of a diagram as shown in figure 7.1. The opportunity window is the period within which the defect could have been identified by inspection and corrective action taken before it led to a failure. The delay time h, reflects the characteristic of the plant/system.

Identifying the opportunity window in a system is important to minimise the number of failures. As an example, consider figure 7.2 where a system is operated with a maintenance period of 6 months. Plotting the failures on the same time scale as the inspection activities, it can be seen that if the inspection period was reduced from every 6 months (A) to every 3 months (B), the failures would not have happened, as it would have been detected during the inspection and necessary repairs would have been carried out.

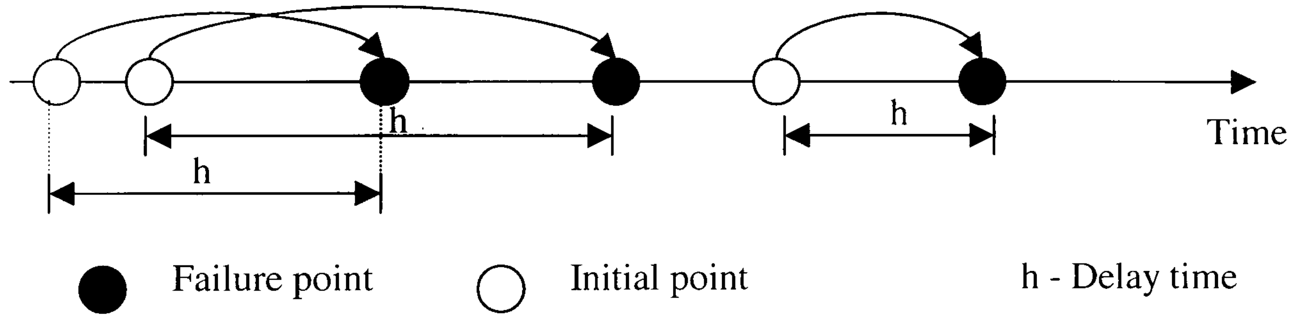

Figure 7.1 Delay time

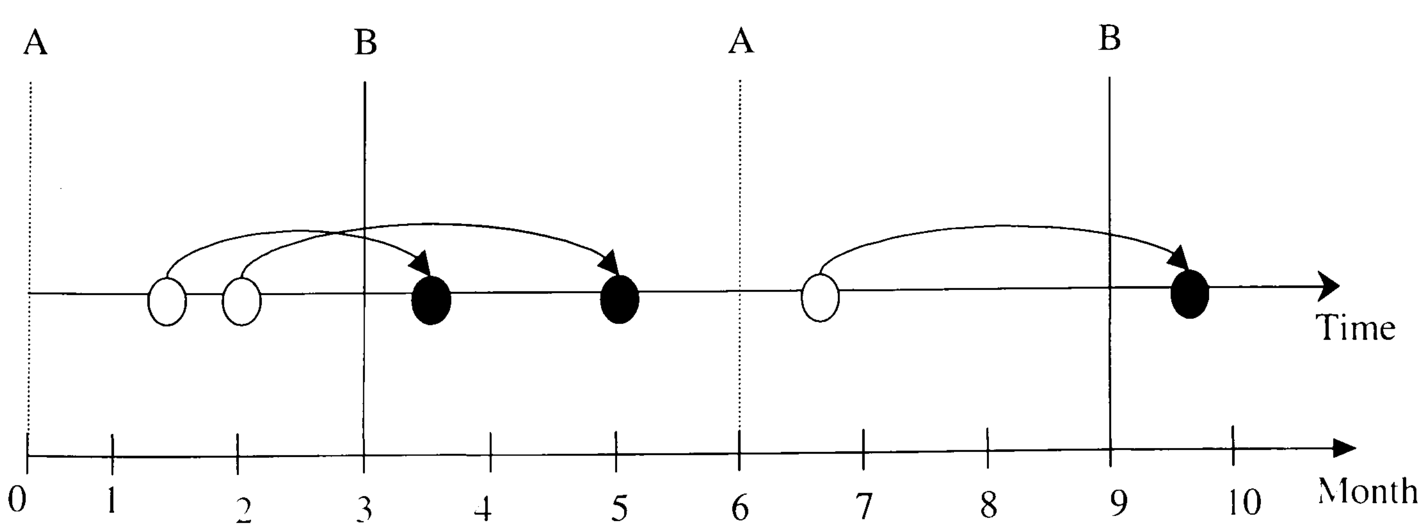

Figure 7.2 Inspection every 6 months (A) and 3 months (B)

risks involved as a result of marine transportation of hazardous material such as liquefied gasses and radioactive substances. It is expected that recent legislation in relation to the control of major hazards will result in a wider use of quantitative safety assessment methods and this will inevitably involve the marine industry.

Offshore installations can be associated with high-risk petrochemical installation and most chemical and petrochemical companies in the UK have made use of reliability techniques for safety assessment, plant evaluation and planning. Similar methods are regularly employed in relation to offshore production and exploration installations.

The Royal Navy has introduced reliability and maintainability engineering concepts in order to ensure that modern warships are capable of a high combat availability at optimum cost [Gosden S.R and Galpin L.K, 1999]. The application of these methods has been progressively extended from consideration of the operational phase and maintenance planning to the design phase.

To date, comparatively little use of safety and reliability assessment methods has been made in connection with merchant shipping. Lloyd's Register of Shipping has for a long period, collected information relating to failures and has carried out development work to investigate the application of such methods to the classification of ships. Apart from this, some consultancy work has also been carried out on behalf of ship owners. One example is the *P&O Grand Princess,* for which a comprehensive safety and availability assurance study was carried out at the concept design stage of this cruise ship. Established risk assessment techniques were used including Failure Mode and Effects Analysis (FMEA), flooding risk analysis and fire risk analysis. The resultant ship was believed to be better and safer than it would have been otherwise [Best P.J. and Davies W.B., 1999]. P&O have now developed an in house safety management system which is designed to capture any operational feedback, so as to improve the safety and efficiency of their cruise fleet operation and to use it for better design in the future.

The merchant ship-building yards in the UK, having seen the success of the warship yards in applying Availability, Reliability and Maintainability (ARM) studies at the

Following the argument of Christer and Walker [Christer A.H. and Walker W.M., 1984c], a fault arising within a period (0,T) has a delay time, h and f(h) is the probability distribution function of the delay time. A fault will be repaired as a breakdown repair if the fault arises in the period (0, T-h); otherwise an inspection repair as seen in figure 7.3.

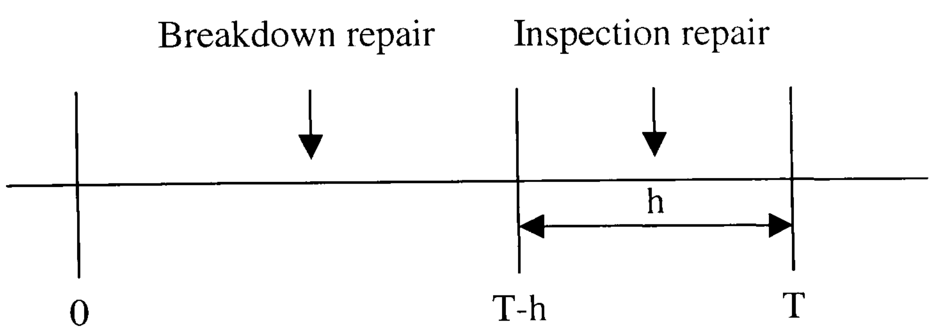

Figure 7.3 Breakdown and inspection repair

Summing up all possible values of h, the probability of a defect arising as a breakdown failure b(T) can be expressed as:

$$b(T) = \int_0^T \frac{(T-h)}{T} f(h)\,dh \qquad (1)$$

where T is the inspection period and f(h) is the probability distribution function of the delay time. An estimation of the probability distribution function can be achieved in several ways as discussed in section 7.3.1.

7.3 A Proposed Approach

The flowchart in figure 7.4 illustrates the proposed approach to delay-time analysis of fishing vessels. The proposed approach is an integration of three models, that is the downtime estimation model, cost estimation model and safety criticality estimation model.

These models require failure data and a probability distribution function of the delay time. The data is then used in a mathematical formula to generate various values for the inspection period, T for corresponding expected downtime D(T), expected cost C(T) and expected safety criticality S(T). Each model developed will produce an optimal inspection period such that downtime, cost or safety criticality is minimised. A best compromise is then achieved by plotting D(T), C(T) and S(T) against the inspection time, T.

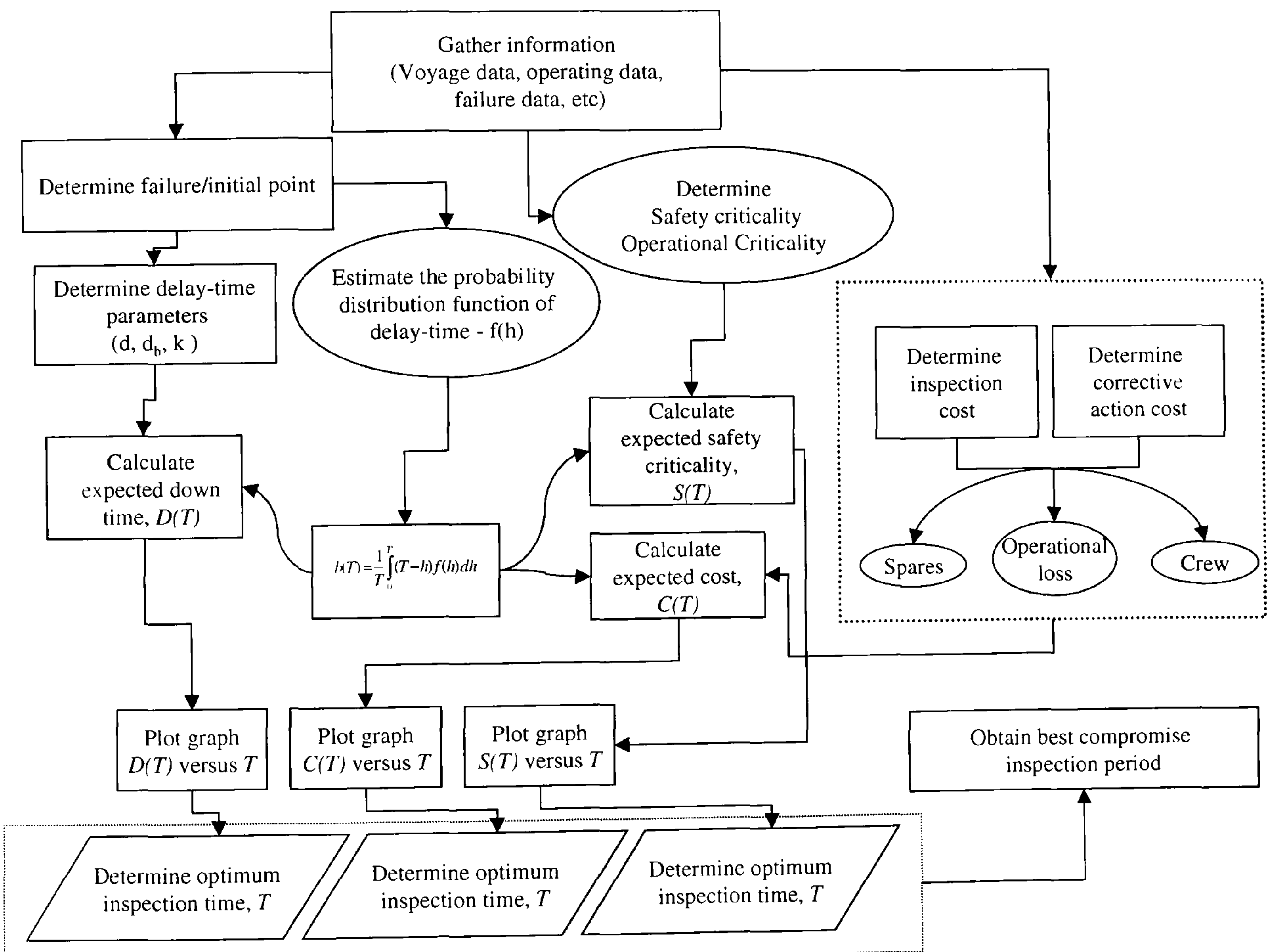

Figure 7.4 Proposed approach flowchart

7.3.1 Expected downtime model

After studying the operating practice, the existing maintenance and failure data, the system can be modelled using the following assumptions:

- Inspections take place at regular time intervals of T hours and each requires a constant time.
- Downtime owing to inspection = d
- Average downtime for breakdown repair = d_b
- Arrival rate of defects per unit time = k
- Inspection period = T
- Failures are repaired immediately with downtime $d_b << T$
- Inspections are perfect in that any defect present will be identified.
- Defects identified will be repaired within the inspection period.
- The time of origin of faults is uniformly distributed over the time between inspections.
- The delay time is independent of its time of origin.

As a consequence of the above assumptions, the model of b(T) given in equation (1) can be simplified as:

$$b(T) = \frac{1}{T}\int_0^T (T-h)f(h)\,dh \qquad (2)$$

Consequently, the expected downtime per unit time function D(T) is given by equation (3) below:

$$D(T) = \left\{\frac{d + kTb(T)d_b}{T+d}\right\} \qquad (3)$$

Substituting b(T), from equation (2) gives:

$$D(T) = \left\{\frac{d + kT\left[\frac{1}{T}\int_0^T (T-h)f(h)\,dh\right]d_b}{T+d}\right\} \qquad (4)$$

Delay time parameter estimation

Delay time distribution can be predominantly estimated using subjective or objective methods. Several models have been developed for these two approaches [Baker R.D. and Wang W., 1992; Baker R.D. and Wang W., 1993; Wang W., 1997]. The objective models generally require a large amount of data complemented with survey questionnaires, which should reflect the operations of the analysed system over a considerable period of time. These requirements however, are difficult to fulfil when considering operating systems on board fishing vessels. The subjective models would be more suitable for the intended application, however, these methods are complex, resource intensive and time consuming. As such, for demonstration purposes, different known distribution functions are experimented to determine the distribution function that produces the best results. As it will be demonstrated later, the research indicates that a truncated standard normal distribution and a weibull distribution are the most appropriate for dealing with failure data of fishing vessel systems. The truncated standard normal distribution is then used to determine the optimum inspection period for the expected cost and safety criticality model.

When the probability distribution function of the delay time, *f(h)*, follows the normal distribution, i.e.

$$f(h) = \frac{1}{\sqrt{2\pi\alpha}} e^{-(h-\mu)^2/2\sigma^2} \qquad (5)$$

where μ = mean and σ^2 = standard deviation of h.

Care is necessary when using the normal distribution, since h $\geq$ 0, there is always a positive chance with the normal distribution that the observation is negative. Hence, a truncated standard normal distribution would be more appropriate.

Let $\mu = 0$ and $\sigma^2 = 1$, assuming a truncated standard normal distribution, equation 5 is simplified to become:

$$f(h) = \frac{2}{\sqrt{2\pi}} e^{-h^2/2} \qquad (6)$$

Substituting equation (6) into equation (4) gives:

$$D(T) = \left\{ \frac{d + kT\left[\frac{1}{T}\int_0^T (T-h)(\frac{2}{\sqrt{2\pi}}e^{-h^2/2})dh\right]d_b}{T+d} \right\} \quad (7)$$

Equation (7) will give the estimated downtime per unit time of the equipment. A practical way of expressing this downtime is by means of its availability within a specified time period. The availability of the system, A, is calculated using equation (8):

$$A = \frac{TOT - TDT}{TOT} \quad (8)$$

where

TOT = Total operating time

TDT = Total downtime

The total downtime can be estimated using equation (9) below:

$$TDT = \left(\frac{TOT}{T^*}\right)\left[d + kT^* bT^* d_b\right] \quad (9)$$

where

T^* = Optimum inspection period (when downtime is minimised)

The optimal inspection period, T, can be obtained graphically by plotting for equation (7) the expected downtime, D(T), against the inspection period, T. The optimal period will be such that D(T) is minimised or alternatively, such that the availability is maximised. The point availability obtained from the proposed method only reflects the availability of the component analysed and does not account for any redundancy features incorporated within the system.

7.3.2 Expected cost model

This model estimates the expected cost per unit time of maintaining the equipment on an inspection regime of period T. The probability of a defect arising as a breakdown failure is given in equation (1) as b(T). As an inspection repair cost applies to all components even if the component is in good condition, the probability of fault arising as an inspection repair is 1 - b(T).

There are three cost elements which needs to be considered in this modelling phase. These three elements are:

- Cost of a breakdown.
- Cost of an inspection repair.
- Cost of an inspection.

Using the same assumptions and notations described in section 7.3.1, equation (4) is modified to include the various costs involved in an inspection maintenance regime to give:

$$C(T) = \frac{[kT\{Cost_B b(T) + Cost_{IR}[1 - b(T)]\} + Cost_i]}{(T + d)} \qquad (10)$$

where:

C(T) = The expected cost per unit time of maintaining the equipment on an inspection system of period T.

$Cost_B$ = Breakdown repair cost.

$Cost_{IR}$ = Inspection repair cost.

$Cost_i$ = Inspection cost.

The above terms are described in detail later. When the probability distribution function of the delay time, *f(h)*, follows a truncated standard normal distribution as shown in equation (6) and substituting this into equation (10) to obtain an expression for the expected cost, C(T) will give:

$$C(T) = \frac{[kT\left\{Cost_B\left[\frac{1}{T}\int_0^T (T-h)(\frac{2}{\sqrt{2\pi}} e^{-h^2/2})dh\right] + Cost_{IR}\left\langle 1 - \left[\frac{1}{T}\int_0^T (T-h)(\frac{2}{\sqrt{2\pi}} e^{-h^2/2})dh\right]\right\rangle\right\} + Cost_i]}{(T+d)} \qquad (11)$$

Breakdown Repair Cost ($Cost_B$)

When considering the cost associated with the breakdown of machinery, all failure modes and consequences need to be known. This can be achieved with the use of a FMEA. The process of carrying out an FMEA can be found in chapter 3 (section 3.11) and a modified FMEA specific for fishing vessels is presented in chapter 6. Using the results from this analysis, each consequence is then quantified in monetary terms. The breakdown repair cost includes costs associated with the effects of a failure and also costs associated with the corrective action taken to restore the equipment back to its working condition. This can be represented by equation (12) below:

$$\boldsymbol{Cost_B = Cost_k^{effect} + Cost_k^{c}} \qquad (12)$$

$\boldsymbol{Cost_k^{effect}}$ is the cost associated with the effect of an equipment failure and $\boldsymbol{Cost_k^{c}}$ is the cost associated with the corrective action carried out on the failed equipment. The various factors considered in predicting the costs associated with the effects of a failure are given in equation (13) and where necessary, it is further elaborated. The various costs involved in carrying out corrective action are given in equation (19) and is explained later.

Predicting costs associated with the effects of a failure

The cost associated with the effect of an equipment failure, $\boldsymbol{Cost_k^{effect}}$, is given by:

$$\boldsymbol{Cost_k^{effect} = \Sigma^n{}_{m=1} (Cost_m^{q}\, \theta_{mk} \varepsilon_k q_k \delta_k^{PF} + Cost_m^{\omega} \theta_{mk} \varepsilon_k \omega_k \delta_k^{PF})} \qquad (13)$$

where

$\boldsymbol{Cost_m^{q}}$ = Cost rate for effect m.

$\boldsymbol{Cost_m}^{\boldsymbol{\omega}}$ = Cost per occurrence for effect m.

$\boldsymbol{\theta_{mk}}$ = Redundancy factor for failure k and effect m.

$\boldsymbol{\varepsilon_k}$ = Operating time factor for failure k.

$\boldsymbol{q_k}$ = Mean probability of failure k.

$\boldsymbol{\delta_k^{PF}}$ = P-F factor for failure k.

$\boldsymbol{\omega_k}$ = Mean frequency of failure k.

The cost rate or cost per hour indicates the estimated cost per unit time due to the occurrence of the effect. The cost per occurrence indicates the fixed cost incurred every time the effect takes place.

The redundancy factor indicates whether a cause will produce the assigned effect on its own or whether other concurrent failures will need to occur for the effect to take place. A redundancy factor often needs to be determined if the effect is a hazardous effect as there will almost certainly be protective systems in place to mitigate against failures, which would lead to a hazard. If the cause will produce the assigned effect without other concurrent failures taking place then the default value of 1 should be assigned to the redundancy factor. If the cause will only produce the assigned effect when other concurrent failures occur (e.g. protective equipment is unavailable) then a factor of between 0 and 1 should be applied. The redundancy factor represents the probability that the failure cause will produce the assigned effect. For example, consider the analysis of the failure cause, 'valve stuck closed' in a hydraulic winch system. This failure might lead to a hazardous event unless the system was shut down until the repair could be effected. The protection system provided to protect against the hazardous event might consist of sensors and alarms and require the intervention of automatic shut-down systems and operator actions. If the protection system were to fail then the hazardous effect would occur, the unavailability redundancy factor should be set to the estimated probability that the protection system would not work on demand. Therefore, if the probability of failure of the protection system is estimated at 0.0001, the redundancy factor should be set to 0.0001.

The operating time factor indicates the fraction of the system lifetime or sampling period for which the specified failure effects are applicable. If the failure mode will always result in the specified effects then this factor should be set to 1. If the system operates in different phases, and the effects of failure are only applicable during certain phases then this value should indicate the ratio of applicable phase time lengths to the total lifetime:

$$\varepsilon_k = \tau_A / \tau_L \qquad (14)$$

where

ε_k = operating time factor.

τ_A = sum of applicable phase time lengths.

τ_L = system lifetime/sampling period.

The potential failure (P-F) interval indicates the time period before an actual failure during which potential failures are revealed. If the P-F interval is set to zero, failures will only be revealed if they have already occurred. Inspections of items with P-F intervals of zero are only effective for hidden failures. If potential failures can be identified before they occur (P-F interval > 0) then it may be worth inspecting items with revealed failures at regular intervals. The P-F factor is used to model the effects of non-zero P-F intervals for inspection tasks and alarm monitoring. For inspection tasks, the P-F factor is given by:

$$\delta_{PF} = 1 - i_{PF} / (\tau_i + mttr) \;\; for\; i_{PF} / (\tau_i + mttr) < 1 \qquad (15)$$

$$\delta_{PF} = 0 \;\; for\; i_{PF} / (\tau_i + mttr) \geq 1 \qquad (16)$$

where

i_{PF} = P-F interval for the inspection task

τ_i = Inspection interval

$mttr$ = Corrective outage duration (including logistic delay)

For condition alarms with non-zero P-F intervals the P-F factor is given by:

$$\delta_{PF} = 1 - i_{PF} / mttr \ for \ i_{PF} / mttr < 1 \qquad (17)$$

$$\delta_{PF} = 0 \ for \ i_{PF} / mttr \geq 1 \qquad (18)$$

In all other cases the P-F factor is set to 1.

Predicting costs associated with corrective action ($Cost_k^c$)

The cost associated with the corrective action carried out on the failed equipment, $Cost_k^c$, is given by:

$$Cost_k^c = Cost_k^{opc}\,\omega_k + Cost_k^{cre,q}\,\omega_k mttr_c + Cost_k^{cre,\omega,c}\,\omega_k + \Sigma^n_{m=1} Cost_{mk}^{spa} U_{mk}^c\,\omega_k \qquad (19)$$

where

$Cost_k^{opc}$ = operational cost for corrective maintenance for failure k.

$Cost_k^{cre,q}$ = cost rate for crew.

$mttr_c$ = corrective task duration.

$Cost_k^{cre,\omega,c}$ = corrective call-out cost for crew.

ω_k = mean frequency of failure k.

$Cost_{mk}^{spa}$ = corrective spare m unit cost.

U_{mk}^c = no of spares used of type m during one corrective task.

The operational cost parameter indicates any costs associated with the maintenance task other than the maintenance crew cost. This parameter is used to indicate any operational costs incurred by taking items off-line during maintenance.

The cost rate defines the cost when the maintenance crew is performing scheduled or non-scheduled maintenance or inspection tasks. The corrective call-out cost represent any fixed costs associated with the call-out of the maintenance crew for corrective repairs. The scheduled call-out cost represent any fixed costs associated with each scheduled maintenance or inspection action.

design stage, are actively seeking benefits from adopting a similar approach. Joint industry-university research projects are being undertaken to explore this area.

1.4 Databases

The early reliability studies, particularly on electronics, made use of failure data obtained by testing a large number of components. As the techniques found more widespread application, the methods for statistically analysing data from real life experience became more advanced and large communal databases of reliability data were created.

In the 1980's, the maritime classification societies, commercial institutions and other authorities realised the importance of statistical data collection on failure or repair data and eventually, data on general accident statistics were provided [Home Office, 1990; Health and Safety Executive, 1992a; Health and Safety Executive 1992b]. These data give general trends and are not directly useable in quantitative assessments. By far the most useful sets of statistics on marine accidents are presented in the publications of the UK Protection and Indemnity (P&I) Club of insurers [P&I Club, 1992].

Accident investigation is a common method used by many organisations in attempt to enhance safety. Discovering the causes of casualties may allow steps to be taken to preclude similar accidents in the future. Since 1981 the United States Coast Guard (USCG) has maintained a computer database summarising the causes of investigated marine casualties. In 1992 the USCG implemented a new computer casualty database, the Marine Investigation Module (MINMOD), which changed the way marine casualty investigations were reported [Hill S.G. et. al., 1994]. The new system implemented several improvements that were expected to enhance the validity and completeness of the casualty data reported. One of the most important changes made was the adoption of a chain-of -events analysis of accident causes, enabling a more complete description of all accident-related events and their associated causes.

Inspection Repair Cost ($Cost_{IR}$)

The inspection repair cost will include all the expenses incurred to carry out the inspection and corrective action taken (if necessary). This will include the cost of maintenance engineers, spares consumed and loss of operational time. The expected cost for corrective action under inspection repair is less compared to breakdown repair (from experience of maintenance engineers and ship owners/operators). This is due to the number of components that have to be overhauled/changed when a breakdown occurs, probably attributed to the 'knock-on effect' of a component/machinery failure. Hence, the inspection repair cost is given by equation (20) and the value of $\boldsymbol{Cost_k^c}$ in this equation will be less than the value of $\boldsymbol{Cost_k^c}$ in equation (19).

$$\boldsymbol{Cost_{IR} = Cost_k^i + Cost_k^c} \qquad (20)$$

where $\boldsymbol{Cost_k^i}$ is the cost associated with inspection tasks and $\boldsymbol{Cost_k^c}$ is the cost associated with corrective action.

Predicting Costs Associated with Inspection Tasks ($Cost_k^i$)

The cost associated with inspections carried out on the equipment, $\boldsymbol{Cost_k^i}$, is given by:

$$\boldsymbol{Cost_k^i = Cost_i^{op,g} + Cost_k^{cre,q} mtti + Cost_k^{cre,\omega s}} \qquad (21)$$

where

$\boldsymbol{Cost_i^{op,g}}$ = operational cost for task group i (includes inspection task for failure k)

$\boldsymbol{Cost_k^{cre,q}}$ = cost rate for crew.

$\boldsymbol{mtti}$ = inspection duration.

$\boldsymbol{Cost_k^{cre,\omega s}}$ = scheduled call-out cost for crew.

The inspection duration indicates the mean time taken to inspect the item. This time is only used to calculate the maintenance crew costs. A task group is used to group together different maintenance tasks, which are to be performed at the same time.

Performing an inspection task on a group of items at the same time can often be more cost effective than inspecting the items at different intervals. The values of the cost rate for crew and scheduled call-out cost for crew should be the same as the values used in equation (19).

7.3.3 Expected safety criticality model

This model estimates the safety criticality per unit time of the equipment when it is inspected with a periodicity of T. If b(t) is the probability of a defect arising as a breakdown failure k then, Cr_k^{safety} is the safety criticality of the said failure and Cr_k^{oper} is the operational safety criticality when the defect does not arise and/or is not a breakdown failure. The estimation of Cr_k^{safety} and Cr_k^{oper} are given by equation (22) and (23) respectively.

$$Cr_k^{safety} = \sum_{m=1}^{n} S_m^{safety} \theta_{mk} \varepsilon_k \delta_k^{PF} \omega_k \qquad (22)$$

where

Cr_k^{safety} = Safety criticality associated with failure k.

$S^{safety}{}_m$ = Safety severity for the m^{th} effect for failure k.

θ_{mk} = Redundancy factor for failure k and effect m.

ε_k = Operating time factor for failure k.

δ_k^{PF} = P-F factor for failure k.

ω_k = mean frequency of failure k.

$$Cr_k^{oper} = \sum_{m=1}^{n} S_m^{oper} \theta_{mk} \varepsilon_k \delta_k^{PF} \omega_k \qquad (23)$$

where

Cr_k^{oper} = Operational safety criticality associated with failure k.

$S^{oper}{}_m$ = Operational safety severity for the m^{th} effect for failure k.

θ_{mk} = Redundancy factor for failure k and effect m.

ε_k = Operating time factor for failure k.

δ_k^{PF} = P-F factor for failure k.

ω_k = mean frequency of failure k.

The safety and operational severity of a failure can be identified by performing an FMEA study on the system. The values of these two parameters can be estimated subjectively using a scale of 0 to10 (0 being least critical and 10 being most critical). The values are assigned based on the probability of occurrence and severity, and are considered for four categories (personnel, environment, equipment and catch). All the other variables in equation (22) and (23) will have the same values as defined in equation (13) of section 7.3.2.

Maintaining the assumptions and notations presented in section 7.3.1, the expected safety criticality is given by equation (24).

$$S(T) = \frac{kTCr_k^{safety} b(T) + Cr_k^{oper}[1 - b(T)]}{T + d} \qquad (24)$$

where S(T) is the expected safety criticality per unit time and Cr_k^{safety} and Cr_k^{oper} is given by equations (22) and (23) respectively.

7.4 An Example

The application of the delay time concept to determine the optimum inspection interval is demonstrated using a main hydraulic winch operating system on a fishing vessel. This vessel is a 1266 GRT (Gross Tonnage), deep-sea trawler with an L.O.A (Length overall) of 60 meters. The winches are used to deploy the nets and haul the catch on to the ship. The supporting winches, that is, the gilson winch and tipping winches are not considered in this example. The schematic diagram in figure 7.5 shows the layout of the main hydraulic piping system and the associated components within the system. The main pumps provide the hydraulic power to the port and starboard winches as well as the net drum motor. The 1010 pumps are used to control the tension and balance the loads on the main winches.

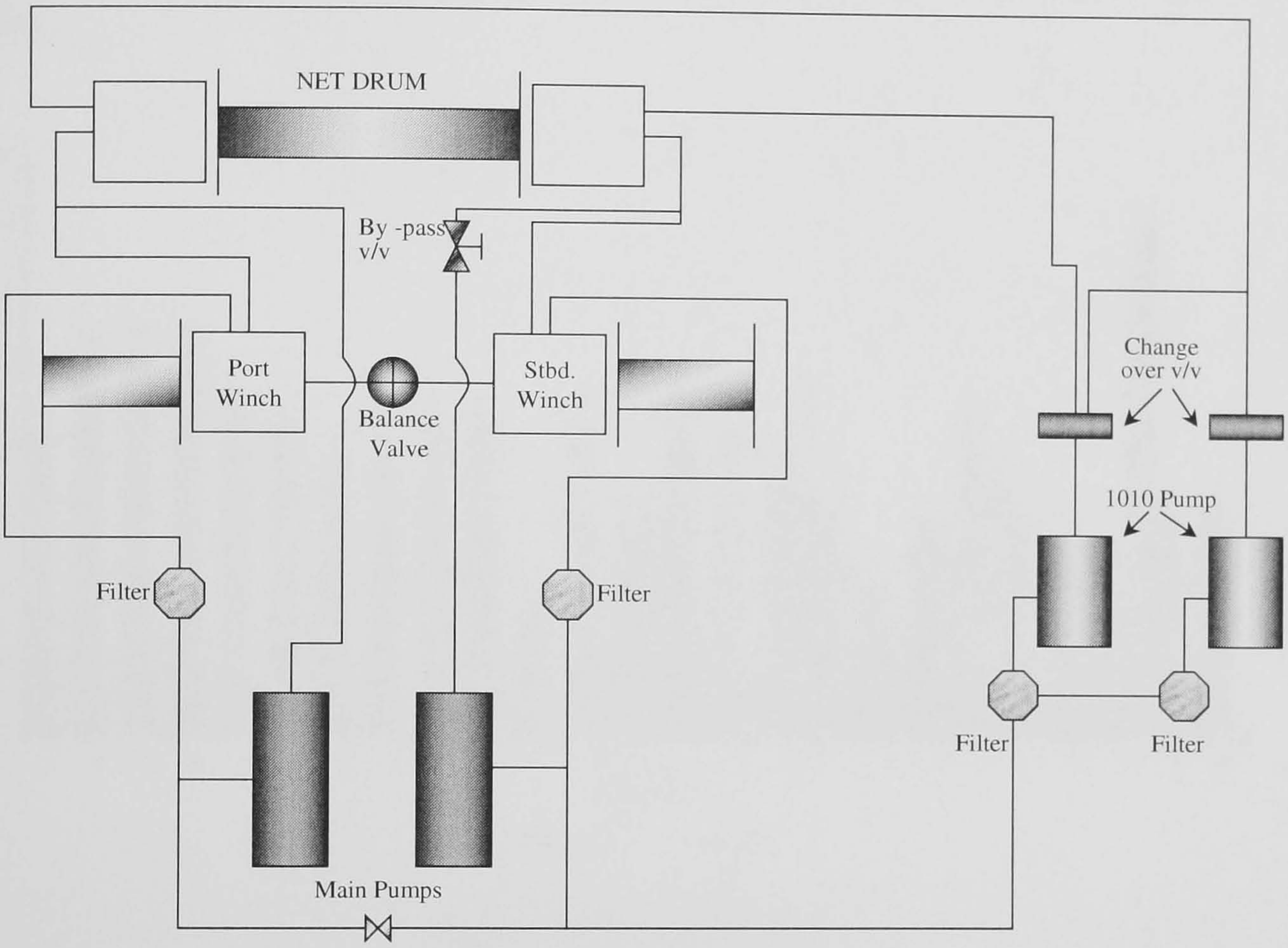

Figure 7.5. Hydraulic winch operating system of a fishing vessel

The fishing vessel used in this test case has a voyage profile as illustrated in the bar chart in figure 7.6. The voyage duration of the vessel depends solely on the success of the catch and the duration at port depends on the discharging time and the amount of work to be carried out on the ship as discussed in section 7.2. As an example of an analysis at the component level, the actual maintenance period and failures of a brake seal for a winch are shown in figure 7.7. This particular vessel operates on a yearly inspection/maintenance regime. This entails that once a year, a thorough check of the vessel is performed. Any components that are identified to require maintenance or replacement (during this inspection) is either overhauled or replaced accordingly to bring the equipment back to "as good as new".

It can been seen from figure 7.7 that many of the failures go unnoticed as the initial point of failure and actual failure occurs between the inspection/maintenance period. For this example, only on two occasions (between voyage 3 and 4 and voyage 10 and 11), the initial failure was detected for the brake seal and the necessary action was taken.

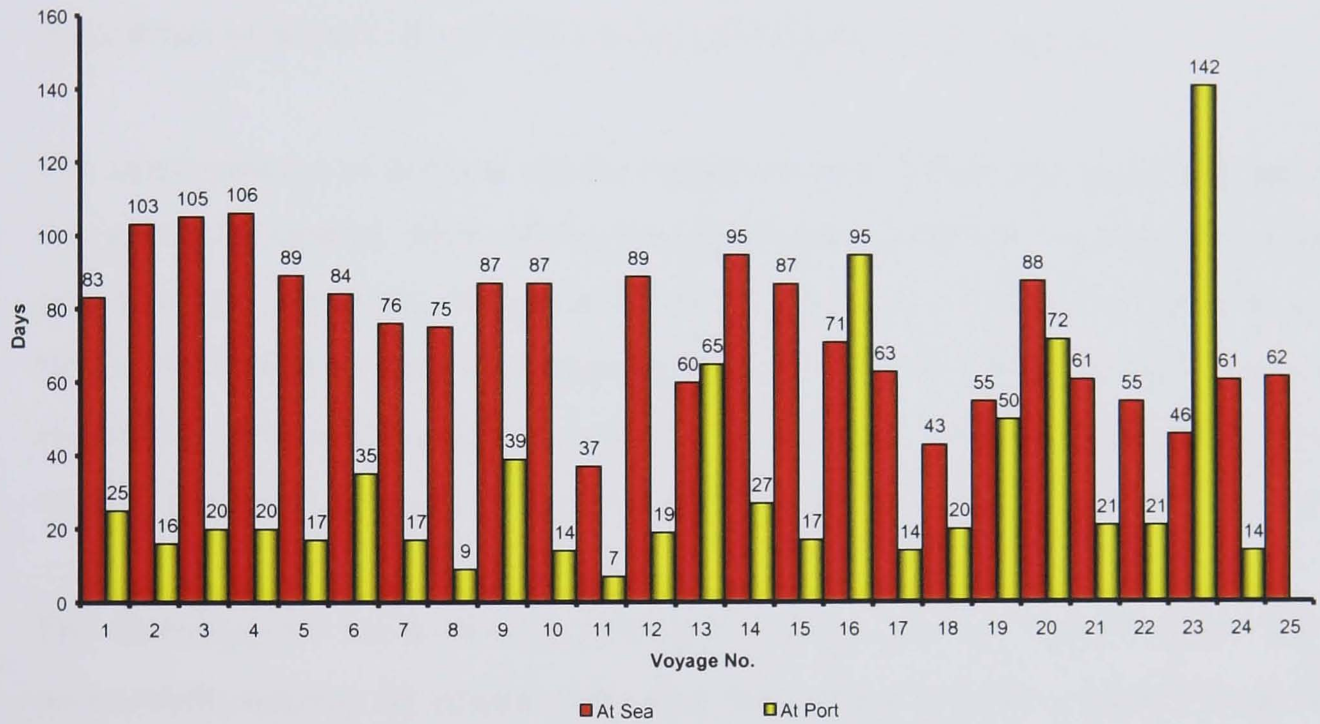

Figure 7.6 Voyage profile

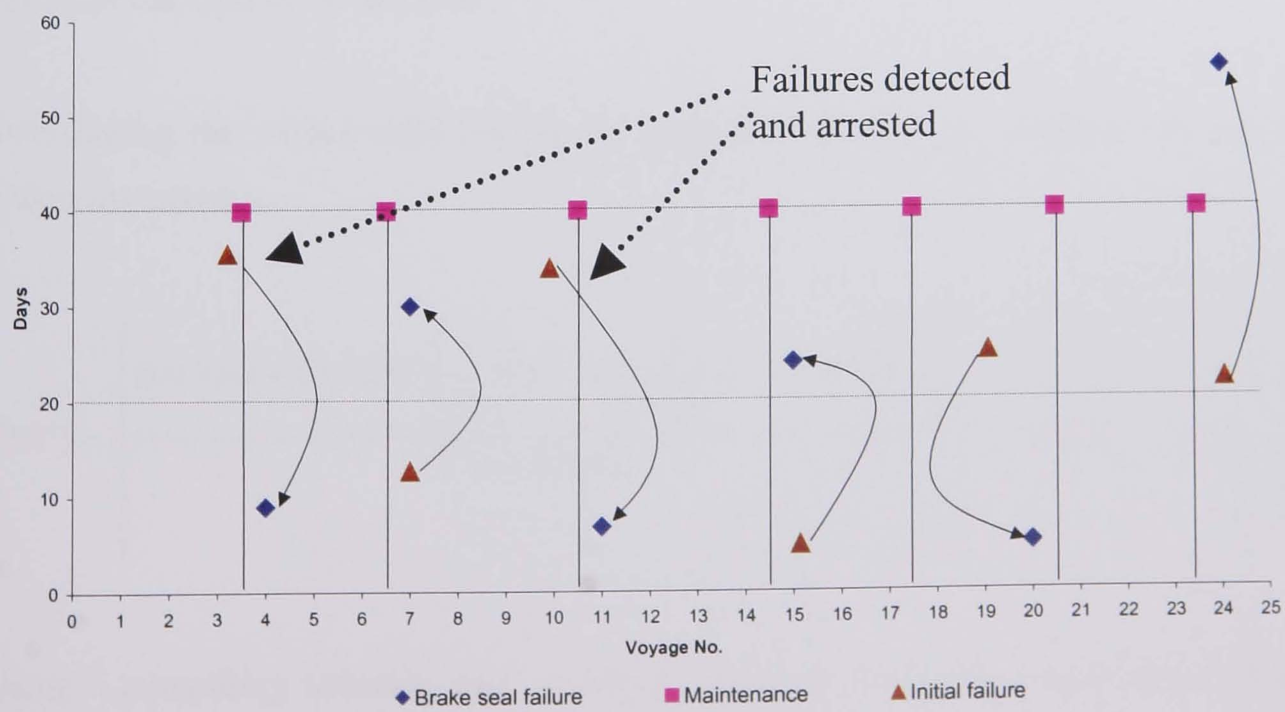

Figure 7.7 Initial point and failure point of brake seal.

The following information was gathered for this particular system, which included a combination of logged records and reports complemented by expert judgements (where no data was available).

Inspection downtime (d) = 15 minutes = 0.01041 days

Downtime for breakdown repair (d_b) = 4.5 days

Total operating hours of winch (for 25 voyages) = 1344 hrs = 56 days

Arrival rate of defects (k) = 0.535 per day [30 failures for 25 voyages]

The actual process of carrying out the inspection itself would take about 45 minutes for this particular system. Most of the inspection can be carried out when the hydraulic system is not operating, this include visual inspection, off-load and function testing. Hence, the downtime caused by inspection would be much lower than 45 minutes. From experience, only 15 minutes is required to carry out an on load pressure test for such a system. Therefore, the inspection downtime, d, is set to be 15 minutes or 0.01041 days.

The downtime for break down repair takes into account any logistic delays that may occur while waiting for spares to be sent from shore suppliers. Most fishing vessels carry minimum amount of spares on board. Hence, should a break down occur at sea on the hydraulic system, the ship might be operationally crippled for a period of time. From experience, this period could be a few of hours or days, depending on the position of the vessel at the time of break down.

Substituting the values obtained for the hydraulic system into equation (7) gives the following equation:

$$D(T) = \left\{ \frac{0.01041 + (0.535T)\left[\frac{1}{T}\int_0^T (T-h)\left(\frac{2}{\sqrt{2\pi}}e^{-h^2/2}\right)dh\right]4.5}{T + 0.01041} \right\} \qquad (25)$$

Using a computing software such as *Derive, MatLab or Studyworks* to solve equation (25), a graph of D(T) against T can be plotted as shown in figure 7.8.

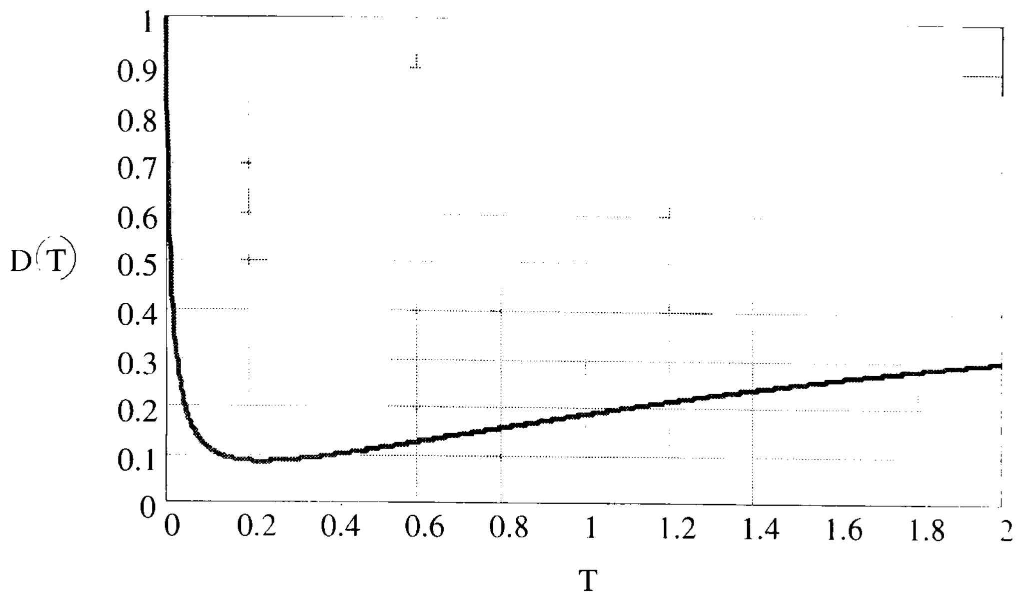

Figure 7.8 Optimal inspection period based on minimum D(T) for a truncated standard normal distribution of the delay time

From the graph in figure 7.8, the optimal inspection period, T (such that the expected downtime is minimised), is determined to be 0.216 days or 5.18 operating hours. This inspection frequency will cause an expected minimum downtime of 0.0853 days or 3.04 hours per unit time. To express this result more clearly for a certain period of operating time, the availability of the equipment is calculated using equation (8) and (9) for various inspection intervals. The total operating time is taken to be 56 days for a period of 25 voyages. The result of this analysis is shown in figure 7.9. From the graph the maximum attainable availability is 91.1% with a corresponding inspection interval of 0.216 days or 5.18 operating hours.

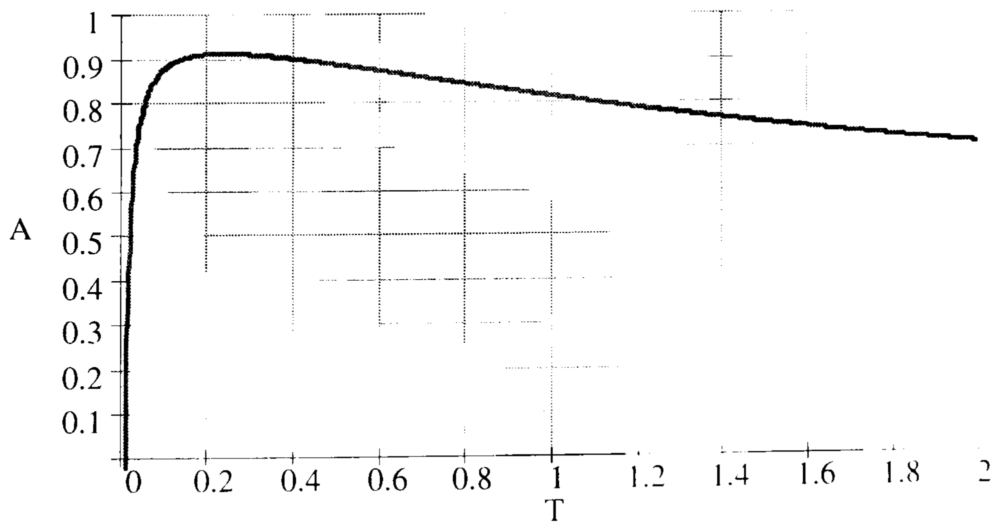

Figure 7.9 Optimal inspection period based on maximum availability for a truncated standard normal distribution of the delay time

For this particular study, two other different probability distribution functions of delay-time were experimented with, namely the weibull distribution and the exponential distribution.

Equation (4) was altered according to the type of distribution used. For the weibull distribution where:

$$f(h) = \frac{\alpha}{\beta} h^{\alpha-1} e^{-(h/\beta)^{\alpha}} \qquad (26)$$

and substituting equation (26) into equation (4) gives the following;

$$D(T) = \left\{ \frac{0.01041 + (0.535T)\left[\frac{1}{T}\int_0^T (T-h)\left(\frac{\alpha}{\beta} h^{\alpha-1} e^{-(h/\beta)^{\alpha}}\right) dh\right] 4.5}{T + 0.01041} \right\} \qquad (27)$$

Different values of α and β were substituted to plot the change in the D(T) versus T curve. The results are as shown in figure 7.10. From these curves, it was determined that the optimum inspection period is between 0.3 to 0.8 days (7.2 to 19.2 operating hours).

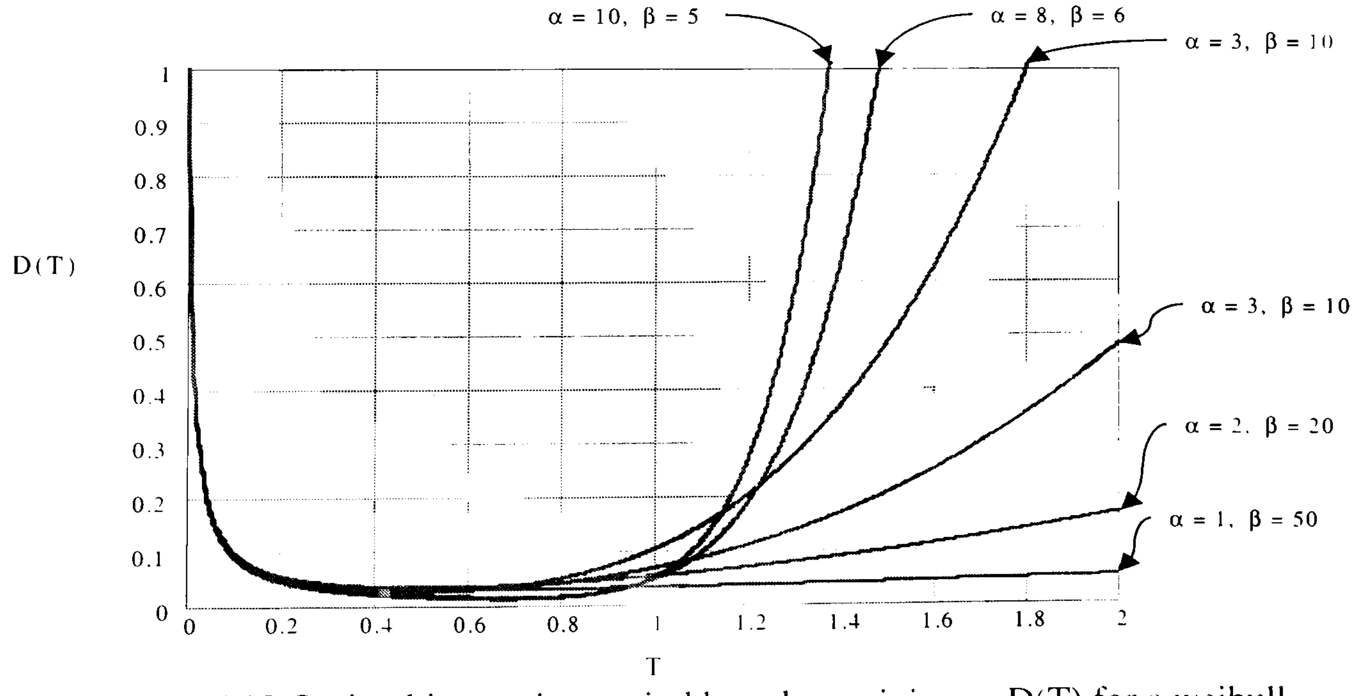

Figure 7.10 Optimal inspection period based on minimum D(T) for a weibull distribution of the delay time

Using the exponential distribution for the delay time, where:

$$f(h) = \lambda e^{-\lambda h} \qquad (28)$$

and substituting equation (28) into equation (4) to obtain an expression for the downtime will give:

$$D(T) = \left\{ \frac{0.01041 + (0.535T)\left[\frac{1}{T}\int_0^T (T-h)(\lambda e^{-\lambda h})\,dh\right]4.5}{T + 0.01041} \right\} \qquad (29)$$

Different values of λ (failure rate) were substituted into equation (29) to produce the graph in figure 7.11. Although different values of λ were experimented with (a range from MTBF=40 to MTBF=900) the curve maintained the same.

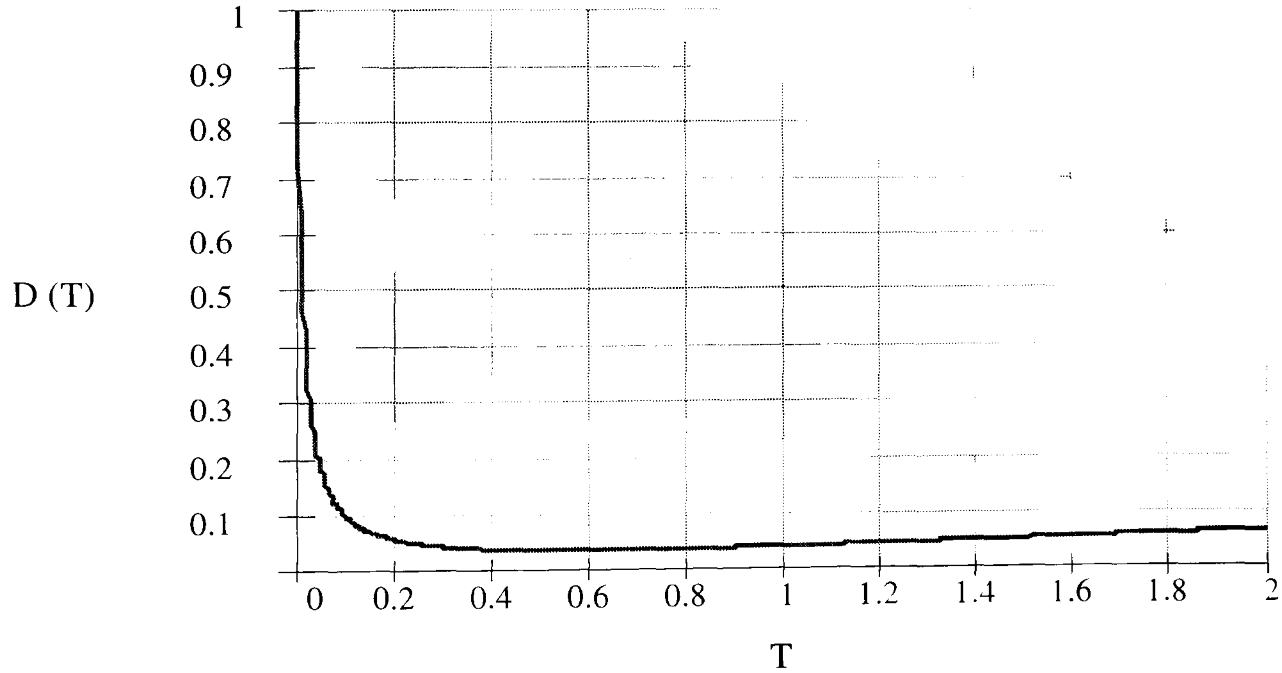

Figure 7.11 Optimal inspection period based on minimum D(T) for an exponential distribution of the delay time

The results obtained using exponential distribution is not very useful as it does not reflect a curve that increases in D(T) as the inspection period increases. From these results, the most suited distribution was found to be the weibull and the truncated standard normal distribution. These two distributions gave clear indications of the optimum inspection period. The values of α and β in the weibull distribution can be estimated by a collection of test data or by using available failure data of the equipment, and since the failure data available is associated with a high degree of uncertainty, this distribution is not used here. As such for the purpose of demonstrating the delay time concept for fishing vessels, the truncated standard normal distribution is used for the expected cost and safety criticality model.

The data collected from the hydraulic system for the cost estimation is as follows:

Cost associated with inspection task ($Cost_k^i$)

From the historical data, it was found that contract workers carry out inspection tasks as per PMS (Preventive Maintenance Schedule) every 365 days when machinery is not operating/at port. However, should the inspection be carried out on board the vessel by the vessel crew, the values for $Cost_i^{op,g}$ and $Cost_k^{cre,q}$ are 0. The only possible cost could be a call out cost for crew to carry out special inspection activities such as, the calibration of pressure control valves on the hydraulic system. The inspection cost from equation (21) is calculated to be:

$$\boldsymbol{Cost_k^i = Cost_k^{cre,\omega,s} = £100}$$

Cost associated with corrective action ($Cost_k^c$)

From the historical data, it is known that contract workers normally carry out corrective action at port upon inspection. However, if the corrective maintenance was carried out on board the vessel upon inspection, the values for $Cost_k^{op}$ and $Cost_k^{cre,q} = 0$. The data used for this test case considers repairs carried out on the clutch seal and break seal of the hydraulic winch. The following parameters were quantified as follows:

$Cost_k^{cre,\omega,c} = £100$

$\omega_k = 2.5$

In the past, accident statistics were not gathered systematically and the data type was not consistent. This led to the analyst not knowing if the set of data is applicable to the analysis under consideration. Some commercial institutions have focused on developing databases of maritime accidents. The accident information is presented systematically and in some cases correlation is available. Typical examples include:

- OREDA (Offshore Reliability Data) - A database of offshore accidents which was first published in 1982 and has been updated annually ever since [OREDA, 1982].
- Marine Incident Database System (MIDS) - A database maintained by the Marine Accident Investigation Branch (MAIB).
- World Casualty Statistics - A collection of data published annually by Lloyds Register of Shipping.
- The Institute of London Underwriters.
- CASMAIN - A database maintained by the United States Coastguard.
- SEAREM - A British Isle database developed and refined under the stewardship of the Royal National Lifeboat Institution (RNLI).

During the last five years, progressive maritime organisations around the world have been cooperating to form a worldwide information network, called RAM/SHIPNET, to support the optimisation of safety, reliability, and cost effectiveness in vessel operations. The mission of RAM/SHIPNET is to form an efficient information network for vessel operators and other industry participants to collect and share sanitised performance information on vessel equipment. It consists of distributed and partially shared Reliability, Availability, and Maintainability (RAM) databases. RAM/SHIPNET was established to collect equipment performance data and to share this data at different levels by linking chief engineers, ship operators/managers, regulatory agencies, equipment manufacturers, and shipyards/designers. First generation stand-alone data collection and processing tools were developed and the system became ready for implementation. The roll-out period is in progress for full validation, demonstration, and implementation of RAM/SHIPNET [Inozu B. and Radovic I., 1999]

The databases that are described in this section, are still lacking specific information of equipment and component failures, novel methods have to be developed to handle this

$Cost_{bseal}^{spa} = £30$

$Cost_{cseal}^{spa} = £30$

$U_{bseal} = 1$

$U_{cseal} = 1$

Substituting these values into equation (19) gives,

$$Cost_k^{c} = 100(2.5) + 30(2.5)(1) + 30(2.5)(1) = \mathbf{£400}$$

The predicted cost associated with inspection repair from equation (20) is calculated to give,

$$Cost_{IR} = 100 + 400 = \mathbf{£500}$$

Cost associated with the effect of equipment failure ($Cost_k^{effect}$)

The failure of the winch has an effect on the personnel, environment, equipment and catch [Pillay A. et. al., 2001]. The cost rate ($\boldsymbol{Cost_m^q}$) and cost per occurrence ($\boldsymbol{Cost_m^{\omega}}$) on each of these categories are given in table 7.2. Since much of the information was lacking, expert judgement and subjective reasoning were used to obtain reasonable estimates of the effects of the hydraulic winch failure.

Effect of failure on	$\boldsymbol{Cost_m^q}$	$\boldsymbol{Cost_m^{\omega}}$
Personnel	£100/hr	£4000
Environment	£100/hr	£2000
Equipment	£100/hr	£1000
Catch	£100/hr	£3000

Table 7.2 Cost rate and cost per occurrence estimation for a failure

The other parameters were quantified as follows:

$\theta_{mk} = 1$

$\varepsilon_k = 1$

$\omega_k = 2.5$

$\delta_k^{PF} = 1$

$q_k = 0.02$

Using these values, the sum of $\boldsymbol{Cost_k^{effect}}$ is calculated from equation (13) to be **£25,000**.

These values are substituted into equation (11) to give the profile of the expected cost, C(T) against the inspection period, T. The results of the analysis are presented in figure 7.12. From the graph, the optimal inspection period for this system is determined to be 0.302 days or 7.24 operating hours and the expected cost at this interval is estimated to be £881.

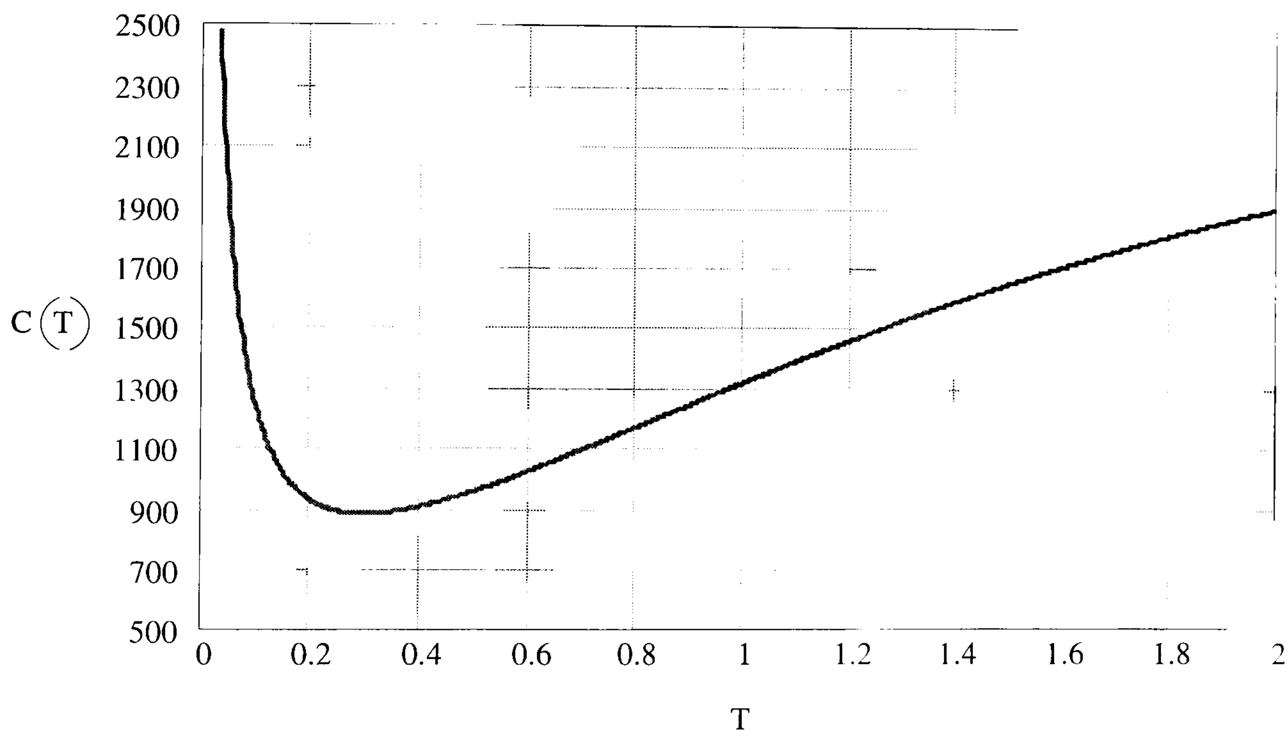

Figure 7.12 Optimal inspection period based on C(T)

To analyse the effect of the change in the cost elements that were difficult to quantify, a sensitivity analysis is performed on the optimal inspection period by altering the inspection repair cost, ($Cost_{IR}$) and the inspection cost, ($Cost_k^i$). The following five cases were considered:

Case 1: $Cost_{IR}$ and $Cost_k^i$ increased by 10%

Case 2: $Cost_{IR}$ and $Cost_k^i$ increased by 5%

Case 3: $Cost_{IR}$ and $Cost_k^i$ unchanged

Case 4: $Cost_{IR}$ and $Cost_k{}^i$ decreased by 5%

Case 5: $Cost_{IR}$ and $Cost_k{}^i$ decreased by 10%

The result of this analysis is shown graphically in figure 7.13 and the expected cost and optimal inspection period for each case is given in table 7.3. From the sensitivity analysis, it can be seen that the optimal inspection period is around 7 to 8 operating hours. The variation in T, is observed to be small when inspection repair cost and inspection cost are varied.

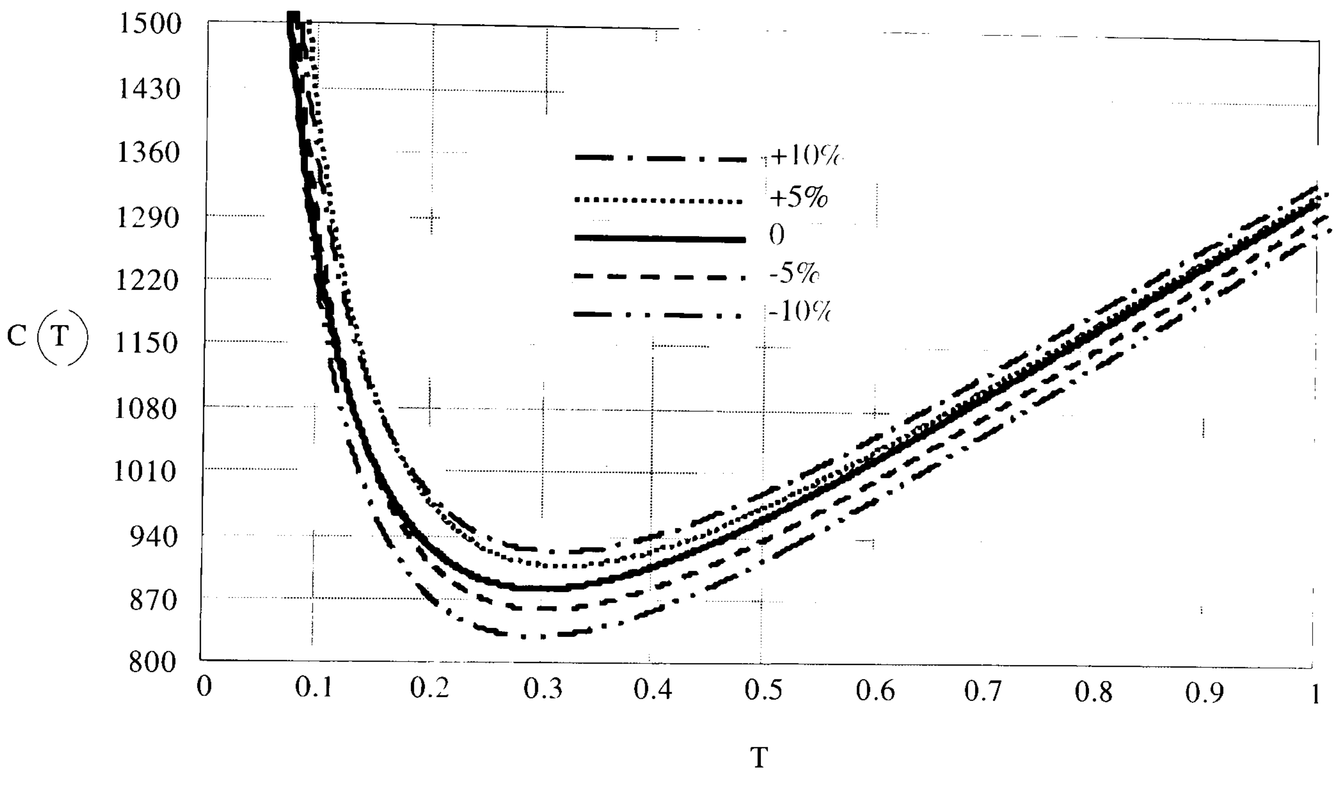

Figure 7.13 Sensitivity analysis for optimal inspection period based on C(T)

Case	*Expected cost, C(T)*	*Optimal insp. period, T (operating hours)*
Case 1 (+10%)	*£938*	*7.92*
Case 2 (+5%)	*£909*	*7.27*
Case 3 (Unchanged)	*£881*	*7.24*
Case 4 (-5%)	*£852*	*7.32*
Case 5 (-10%)	*£822*	*6.94*

Table 7.3 Optimal inspection period based on the sensitivity analysis for various cases

The data collected for the safety criticality estimation is based on expert judgement and is shown in table 7.4. The failure was evaluated for its safety and operational criticality for the four different categories mentioned in section 7.3.3 on a scale of 0 to 10. The estimation of the safety severity parameter (S^{safety}_{m}), is assumed for the worst case scenario. It is also assumed that, if the failure does not lead to a catastrophic breakdown, the operational safety severity (S^{oper}_{m}) will be minimal.

Effect of failure on	S^{safety}_{m}	S^{oper}_{m}	Cr_m^{safety}	Cr_m^{oper}
Personnel	10	1	25	2.5
Environment	10	1	25	2.5
Equipment	10	1	25	2.5
Catch	10	1	25	2.5

Table 7.4 Values of $S^{safety}{}_{m}$ and $S^{oper}{}_{m}$

The values of Cr_k^{safety} and Cr_k^{oper} in equation (22) and (23) were evaluated assuming that θ_{mk}, ε_k, and $\delta_k^{PF} = 1$ and $\omega_k = 2.5$, to give:

$$Cr_k^{safety} = 25 + 25 + 25 + 25 = 100$$
$$Cr_k^{oper} = 2.5 + 2.5 + 2.5 + 2.5 = 10$$

These values are then substituted into equation (24) to give the profile of the expected safety criticality, S(T) against the inspection period, T. The results of the analysis are presented in figure 7.14. This graph indicates than the optimal inspection period when the safety criticality is at its minimum is 0.72 days or 17.28 operating hours. This inspection interval is much higher compared to when the cost or downtime is minimised. This is probably due to the fact that the worst case is assumed for the safety criticality calculation (a score of 10 for all $S^{safety}{}_{m}$).

The next step in the analysis is to determine the best compromise between the three inspection intervals obtained. There are several methods that can be used to determine the best compromise, these include multiple criteria decision making, minimax principle optimisation and the bayesian approach optimisation [Almeida A.T. and Bohoris G.A., 1995]. As these methods require tedious mathematical computation, which is not required here, a simple graphical method is used to determine the best compromise inspection interval.

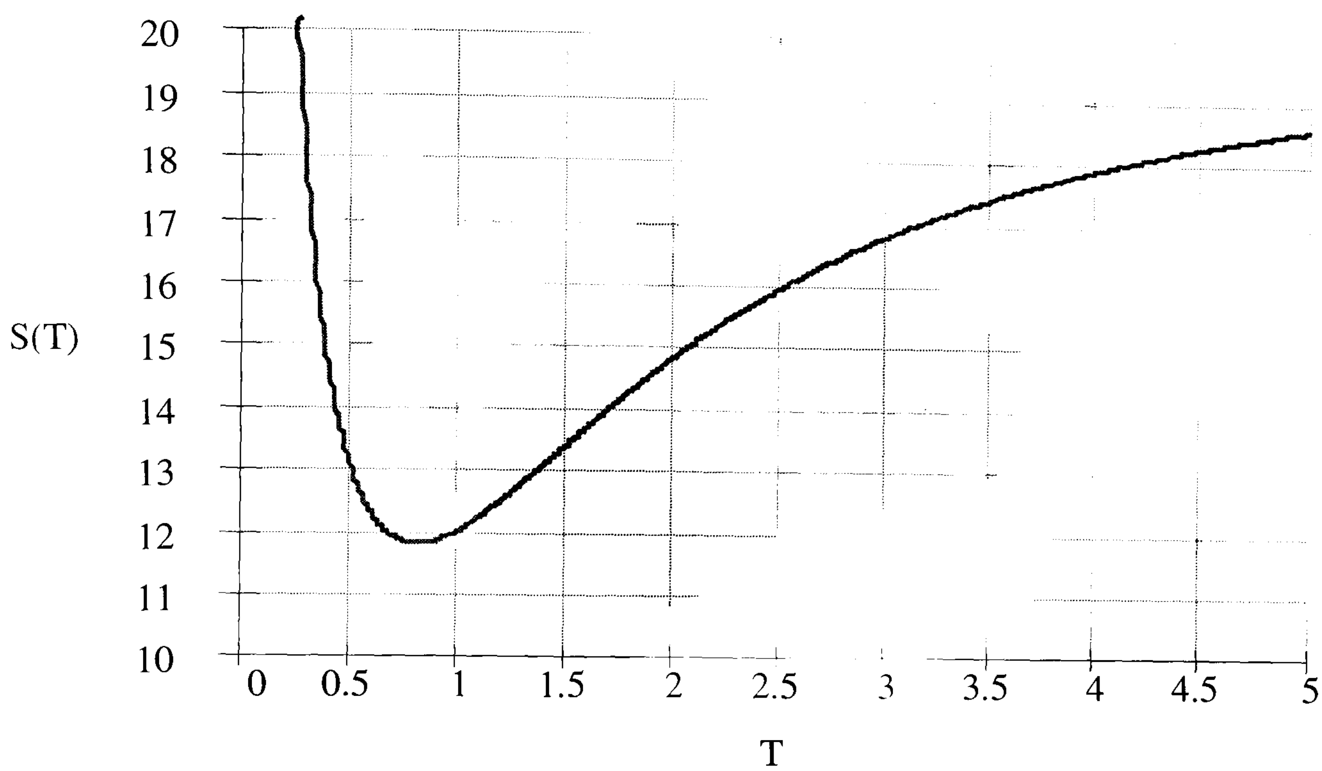

Figure 7.14 Optimal inspection period based on S(T)

7.5 Optimisation Results

The example used to demonstrate the proposed approach generated three different optimal inspection periods. The inspection period is estimated to be 5.18 operating hours when the downtime is minimised, 7.24 operating hours when the cost is minimised and 17.28 operating hours when the safety criticality is minimised. As the change in the safety criticality is small for a large change in the inspection interval, this criterion is not as critical as the cost and downtime criteria. A such, in the first instance the expected cost, C(T) is plotted against the expected downtime D(T) as shown in figure 7.15. The curve generated can be used to determine the best compromise between the cost and downtime criteria.

Points 1 and 2 on the graph show the best downtime and cost achievable respectively for the system with an inspection interval of T^*. Should point 1 be selected, when downtime is minimised the operating cost per unit time is £911. This is almost 3.4% higher than the minimum possible operating cost. However, if point 2 is selected, when the cost is minimised, the downtime suffered will be 0.18 hours per unit time. This translates to a reduction in availability of 0.34% from the maximum availability attainable by the equipment.

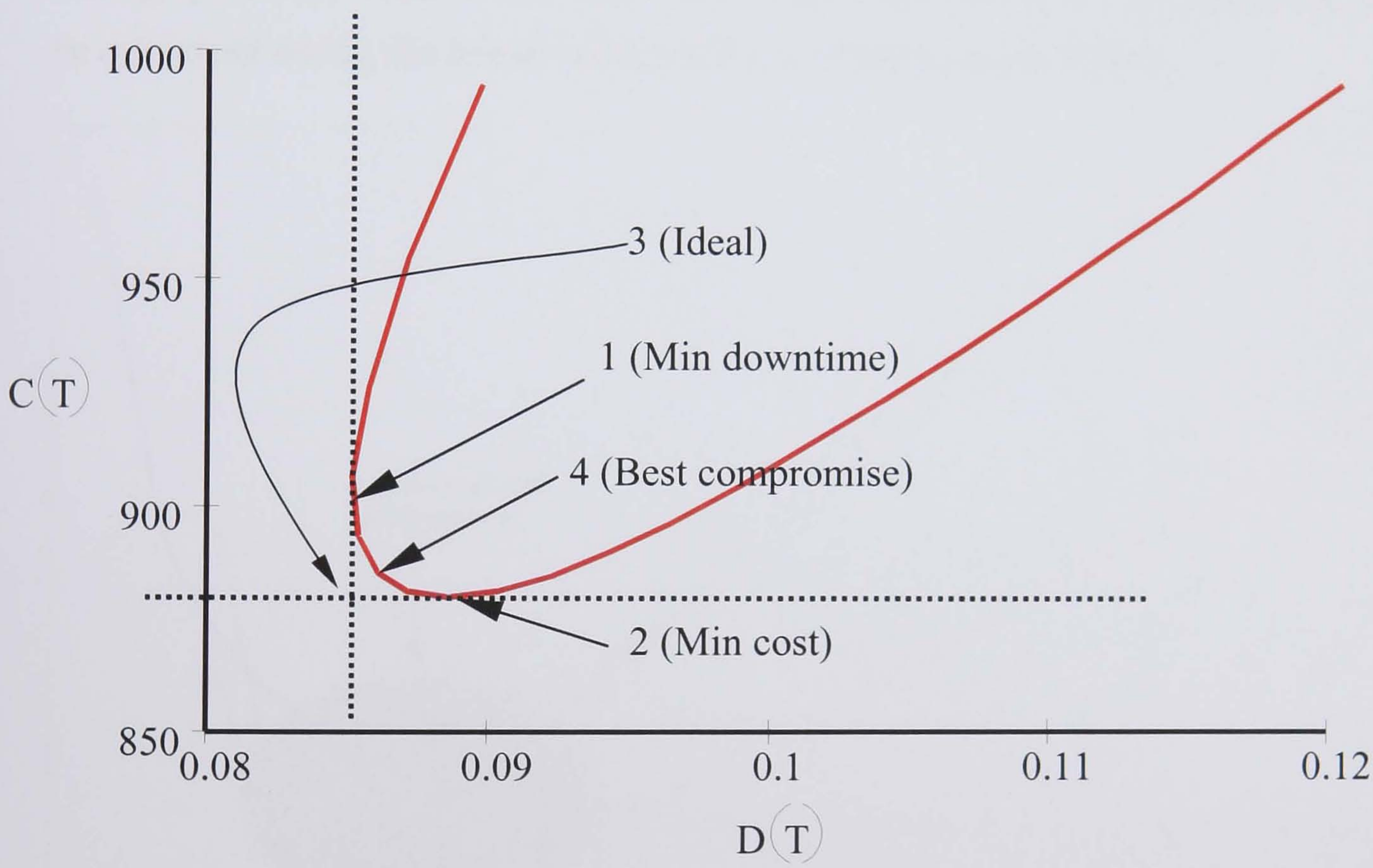

Figure 7.15 Expected cost C(T) against expected downtime D(T)

The ideal inspection time is located at point 3 where both the cost and downtime are simultaneously minimised. However, such an operating condition does not exist for the system that was modelled. Therefore, the best compromise is identified at point 4, which is nearest to the ideal point. If the cost and downtime are of equal importance, the best compromise point can be obtained using minimax approach [Sen P. and Yang J.B., 1993]. From the analysis, the best compromise (point 4) is when the inspection period is 6.24 operating hours, cost is £886, the expected downtime is 2.06 hrs per unit time and the availability of the equipment is 91%. Considering the inspection time interval obtained (6.24 operating hours), it would entail that an inspection is to be carried out after every two fishing operations (assuming that the main winches run on an average of 3 hours per operation).

The graph in figure 7.16 gives a clearer indication of the three criteria modelled for the winch system. This graph plots the expected cost, C(T), expected downtime D(T) and expected safety criticality S(T) against the inspection period T. The shaded area shown on the graph represents the approximate operating hours of the winch system (per fishing operation), which ranges from 3 to 6 hours. For convenience, the inspection can be carried out during this period as the penalty is within acceptable limits.

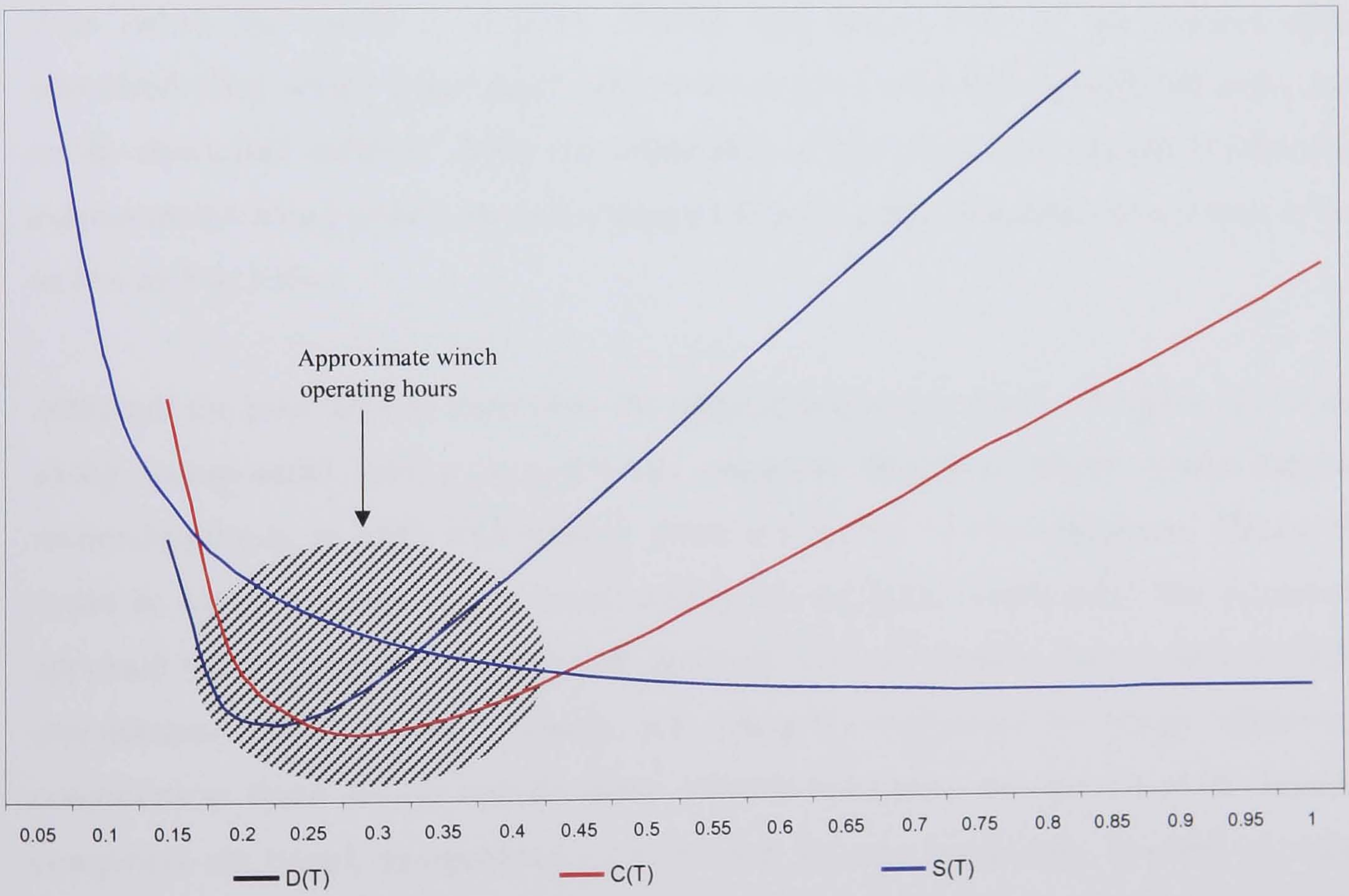

Figure 7.16 D(T), C(T) and S(T) against T

7.6 Conclusion

The use of a delay-time model within a preventive maintenance system would be useful to minimise downtime caused by undetected failures. Inspections carried out during the operation phase of machinery will reveal any failures that have already been initiated at an earlier time. Upon identifying the 'abnormal' condition, necessary action can be taken to arrest the problem before it propagates to become a failure. This chapter demonstrates the delay-time concept with the use of data gathered from a fishing vessel. Assumptions and expert judgements were made where the data was incomplete. Since there was no record of the delay-time for failures, the probability distribution function of the delay-time could not be ascertained mathematically. As such, known distribution functions such as the standard normal, exponential and weibull were used to demonstrate the concept.

The example of the brake seal failure with the current maintenance policy of every 365 days (when the vessel is at port), showed that almost 66% of the failures went unnoticed. This would entail high repair costs coupled with high operational costs due to the downtime suffered. With the integration of the delay-time concept within the current maintenance policy, the percentage of failures going unnoticed is expected to be as low as 5 to 10%.

Although the procedure to determine the optimal inspection time is complex, it can be easily incorporated into a user friendly computer interface, which would require owners/operators to input information about the failure of the equipment. Hence, it could be easily adapted to any vessel within the maritime community. The proposed approach would appeal to owners and operators who are running their vessels at high maintenance costs. Fishing vessels are constantly subjected to rough operating conditions as these vessels operate under various constrains such as size of the vessel, equipment on board, competency of crew and weather conditions. Owners of such vessels would be enthusiastic to incorporate an inspection regime on their fleet, as this would entail a more cost efficient ship, which further translates into income for the company. The proposed approach does not require any condition monitoring equipment to be installed, hence it would not be expensive for the owners/operators to implement such a method.

The inspection regime can be integrated into the existing maintenance procedures in order to minimise the operating cost and downtime suffered. The effectiveness of the proposed approach can be improved if sufficient data is available in order to generate a true probability distribution function for the delay time. Currently there is no procedure in place for testing the hydraulic equipment for operation before the start of a fishing operation. As such, having an inspection regime before every other operation could be very useful to minimise unforeseen accidents/incidents caused by equipment failure. Any inspection regime implemented on board a fishing vessel would enable gathering of useful information about the system, such as the time of actual failure and the time of initial failure (the time when the equipment starts to show signs of abnormalities). This information will enable for better prediction of the delay time interval and distribution, hence, enhancing the accuracy of the model.

The final decision of the optimal inspection period will depend heavily on the needs and operating culture of the owner/operator of the vessel. The implementation of such a regime on fishing vessels will be influenced by the operating circumstances of the equipment and other factors such as availability of expertise, position of vessel and sea conditions. However, should the conditions for implementation be favourable, DTA can be used to optimise the systems' inspection maintenance scheme.

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shortcoming. These novel techniques should integrate expert judgement with available data in a formal manner to ensure the accuracy and the applicability of the safety assessment carried out.

1.5 Description of the Proposed Research

The primary aim of this project is to develop novel safety assessment methods to be applied to fishing vessels. Fishing vessels were chosen as a test case as the vessels are generally smaller with a unique operating nature and the accidents concerning these types of vessels have been overlooked in the past. Most fishing vessels are owner operated and lack the organisational structure of other merchant vessel companies. This leads to the difficulty in gathering accident/failure information for a safety analysis. Since the fishing vessel industry is starved of safety and reliability data, conventional safety and risk assessment techniques are not readily applied. The available quantitative techniques require a certain amount of failure data in order to make a reasonable safety prediction. The novel methods developed in this project will address this set back of the traditional methods by integrating within its model the ability to handle vague and uncertain data in an effective manner to produce a reasonably accurate safety assessment. These novel methods will integrate hazard identification, risk quantification and ranking with formal decision making techniques so that safety improvements made to new as well as existing vessels are effective and justified.

The specific objectives of this project can be summarised as follows:

1. Identify safety assessment techniques currently used in the shipping industry, which include methods of hazard identification, risk quantification, cost benefit analysis techniques and decision-making techniques.
2. Study the existing Formal Safety Assessment (FSA) approach in maritime safety application.
3. Develop a general FSA framework for a generic fishing vessel.
4. Develop novel safety assessment modelling techniques within the FSA framework to facilitate safety assessment of fishing vessels.

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CHAPTER 8

HUMAN ERROR ASSESSMENT AND DECISION MAKING USING ANALYTICAL HIERARCHY PROCESSING

Summary

A brief review of common human error assessment methods is presented highlighting the requirements and steps of each method. This is followed by an introduction to the Analytical Hierarchy Processing (AHP) method to aid decision-making. An approach to integrate human error assessment and decision-making using the AHP method is proposed. The aim of this approach is to reduce the probability of occurrence and severity of human error during the operational phase of a fishing vessel. It utilises AHP theory to rank the impacts of human error and further integrates the available control options (to minimise these errors) within the analysis. The result obtained from the analysis reflects the most favoured control option that will address all the possible human errors within the system to a satisfactory level. A test case, which considers the shooting operation of a beam trawler, is used to demonstrate the proposed approach. Each step involved in the shooting operation is assessed for its vulnerability to human error with respect to the equipment being operated and this captures the operator-machine interaction. The AHP method integrates the evaluation of solutions to reduce risk levels within the human error assessment and this reduces the complexity of the analysis that is present in traditional methods.

8.1 Introduction

The cost of shipping casualties is normally expressed in terms of insurance value. The report of the Institute of London Underwriters (ILU) for 1995 stated that 95 ships were lost during the year [ITSA, 1996; ILU, 1996]. In 1996, the ILU recorded 1,190 lives lost at sea and the ship classification society Det Norske Veritas (DNV) has estimated that accidents on board ships cost the industry around $US 10 billion a year [ILU, 1996;

IMO, 1997]. It has been accepted that 80% of the accidents in the maritime industry is caused by human error. In the fishing vessel industry, Lloyd's Register of World Fleet Statistics 1998 notes that the average age of the world fleet of fish catching vessels over 100 GRT is 20 years [International Transport Workers Federation (ITF), 1999]. This could be a contributing factor to the high level of human error on these vessels. These older vessels lack automation and modern safety devices, hence the safe operation of the vessels is highly dependent on the competency of the crew on board.

Human error has played a critical role in the causes of many major marine accidents. The officers and crew of the Herald of Free Enterprise set to sea with their bow doors open [Sheen N., 1987]. The crew and skipper of the Pescalanza and Sapphire did not close their watertight doors during heavy seas, which led to the sinking of the vessels by flooding [MAIB, 2000].

In these accidents, life, cargo and property had been lost due to the negligence and/or mistakes made by the operators of the system. Understanding errors and system failures are particularly important with respect to "high-consequence" systems. These are open systems whose behaviour has a significant effect not only on the system itself but also on the world outside the system. Hence, there is a need for an effective method to model the risks posed by human error in order to direct the limited resources to solutions that would reduce these risks.

8.2 Review of Human Error Assessment Methods

Engineers have developed a range of tools that can be used to represent and reason about the causes of major accidents [Leveson N., 1995]. For example, time-lines and fault trees have been recommended as analysis tools by a range of government and regulatory bodies. Unfortunately, these well-established techniques suffer from a number of limitations [Johnson C., 1998]. In particular, they cannot easily be used to represent and reason about the ways in which human errors and system failures interact during complex accidents [Hollnagel E., 1993].

8.2.1 Methods for quantification of human failures

Most methods for estimating human reliability were used in nuclear power plants. Such methods include confusion matrix [Fullwood R.R. and Hall R.E., 1988; Gertman D.I. and Blackman H.S., 1994], expert estimation [Gertman D.I. and Blackman H.S., 1994], Time Reliability Curve (TRC) [Dougherty E.M. and Fragola J.R., 1988; Moieni P. et. al., 1994], Maintenance Personnel Performance Simulation (MAPPS) [Fullwood R.R and Hall R.E., 1988; Gertman D.I. and Blackman H.S., 1994], Success Likelihood Index Method-Multi-Attribute Utility Decomposition (SLIM-MAUD) [Fullwood R.R. and Hall R.E., 1988; Gertman D.I. and Blackman H.S., 1994], sociotechnical assessment of human reliability [Gertman D.I. and Blackman H.S., 1994], Technique for Human Error Rate Prediction (THERP) [Dhillon B. S., 1986], Sandia Recovery Model (SRM), INTENT [Gertman D.I. et. al., 1992] and Operator Reliability Calculation and Assessment (ORCA). Of the methodologies given, most deal with misdiagnosis or non-response errors and time dependent probability estimates. The most commonly used techniques are THERP, utilising generic Human Error Probabilities (HEP) from various industries, and SLIM-MAUD, using importance weightings from experts.

8.2.2 THERP

This method provides a mechanism for modelling as well as quantifying human error. It starts off with a task analysis that describes the tasks to be performed by the crew, maintainers or operators. Together with the task descriptions, Performance-Shaping Factors (PSF) such as stress and time available are collected to modify probabilities. The task analysis is then graphically represented in Human Reliability Assessment (HRA) event trees. The HEP for the activities of the task or the branches are read and/or modified from the THERP tables as shown in [Gertman D.I. and Blackman H.S, 1994]. Details on the construction of HRA event trees and also, the COGnitive EveNt Tree (COGENT) to represent cognitive activities and errors associated with human performance were also given in the book. Gertman and Blackman also provide a summary of the steps to approach THERP, which was adapted from the Nuclear

Regulation-NUREG/CR-1278 [Swain A. D. and Guttmann H. E., 1983]. THERP suffers from the following limitations [Reason J., 1990; White D., 1995]:

- It is difficult to represent the variability of human behaviour adequately.
- The technique assumes each task segment can be handled separately.
- It is difficult to combine human and equipment reliability values.
- It is difficult to identify inter-task dependencies.
- The technique is not appropriate for continuous tasks.
- The method does not determine motivation of the individual.
- Analysts have the tendency to model only errors that appear in databases.

8.2.3 Accident Sequence Evaluation Programme (ASEP)

ASEP is a quicker version of THERP and is more conservative. It is a fine screening approach and can be complemented with THERP to warrant more detailed attention in the risk assessment. For a more detailed discussion on ASEP refer to [Swain A.D., 1987].

8.2.4 SLIM-MAUD

The SLIM-MAUD method is centred on the assumption that the failure probability associated with task performance is based on a combination of PSFs that include the characteristics of the individual, the environment, and the task. It further assumes that experts can estimate these failure rates or provide anchor values to estimate them. Refer to [Gertman D.I. and Blackman H.S., 1994] for a description on the steps to take to perform SLIM-MAUD. Included in this discussion are two enhanced methods for the approach. Dougherty and Fragola also provide the mathematics and an example for calculating SLIM-MAUD [Dougherty E.M. and Fragola J.R., 1988]. Davoudian provides an empirical evaluation of SLIM-MAUD and ranking to estimate HEPs, through the use of a simulated manufacturing environment under varying task conditions [Davoudian K. et. al, 1994].

8.2.5 Human Reliability Assessment (HRA)

HRA analyses the relationship between human behavioural tendencies and the work context to provide a better understanding in anticipating human errors, violations and severe system outcomes. This analysis requires a fundamental understanding of:

1. The way humans process information, including their capabilities and limitations at such processing [Wickens C.D., 1992].
2. Human factors and ergonomics design consideration [Sanders M.S. and McCormick E.J., 1987].
3. Skill, rule and knowledge based framework, which describes distinct levels of information processing at which workers perform [Rasmussen J., 1982; Rasmussen J., 1986].
4. Psychosocial considerations that increase the likelihood of performing violations [Centre for Chemical Process Safety (CCPS), 1994].

The primary goals of HRA are to assess the risks attributable to human error and determine the ways of reducing system vulnerability due to human error impact. These goals are achieved by its three principal functions of identifying what errors can occur (human error identification), deciding how likely the errors are to occur (human error quantification), and, if appropriate, enhancing human reliability by reducing this error likelihood (human error reduction). The HRA process can be broken down into several steps as seen below.

Problem definition: This refers to deciding what human involvements are to be assessed (operators failing to deal with emergencies, operators' contribution to maintenance failures etc.)

Task analysis: When the human aspect of the problem has been defined, task analysis can then define what human actions should occur in such events, as well as what equipment and other "interfaces" the operator should use. It may also identify what training (skills and knowledge) and procedures the operators will call upon.

Human Error Identification (HEI): Once the task analysis has been carried out, HEI then considers what can go wrong. The following types of errors are typically considered:

- Error of omission - failing to carry out a required act.
- Error of commission - failing to carry out a required act adequately; act performed without required precision, or with too much or too little force; act performed at wrong time; acts performed in the wrong sequence.
- Extraneous act - not required act performed instead of, or in addition to the required act.
- Error-recovery opportunities - acts which can recover previous errors.

The HEI phase can identify many errors. Not all of these will be important for the study, as can be determined by reviewing their consequences on the system's performance. The ones that can contribute to a degraded system state, whether alone or in conjunction with other hardware/software failures or environmental events (or both together) must next be integrated into the risk analysis.

Representation: Having defined what the operator should do (via task analysis) and what can go wrong, the next step is to represent this information in a form which allows the quantitative evaluation of the human-error impact on the system to take place. It is usual for the human error impact to be seen in the context of other potential contribution to system risk. Human errors and recoveries are usually embedded within logical frameworks such as fault tree analysis and event tree analysis.

Human error quantification: Once the human error potential has been represented, the next step is to quantify the likelihood of the errors involved and then determine the overall effect of human error on the system safety and reliability. The Human Error Probability (HEP) is simply defined as HEP = (Numbers of errors occurred/Number of opportunities for error).

Impact assessment: Once the errors have been quantified and represented in the risk assessment logic trees, the overall system risk level can be calculated. Then it can be determined whether or not the system has an acceptable level of risk. Impact assessments involve determining if the risk element is acceptable as well as which events (human, hardware, software or environmental - or any combination) contribute most to the level of risk. If the human error is a significant contributor to the system risk level, and if the system risk level is calculated to be too high, then the appropriate error will be targeted for error reduction.

Error reduction analysis: Error reduction measures may be derived:

- According to the identified root causes of the error (from the error identification stage).
- From the defined factors that contribute to the errors' HEP.

If error reduction is necessary to reduce the risk to an acceptable level, then following such error reduction measures, several iteration of impact assessments, error reduction and re-quantification may occur until satisfactory risk levels are achieved.

8.3 Human Error Probability

The analysis of many accidents has led to the appreciation that multiple equipment failures and process deviations combined with faulty human decisions and actions are often involved. Safety assessments, therefore, are not complete unless the interactions between equipment failures and human actions are considered. Since human behaviour is complex, and does not lend itself immediately to relatively straightforward reliability models, it is suggested that the following classifications of human interactions (that typically group all activities) need to be considered [Mahn J.A. et. al., 1995]:

- Pre-initiator human interactions involving maintenance, testing, calibration, planning, etc.
- Initiators of accidents that involve operator awareness of potential accident initiators caused by errors in tests, or reconfiguration conditions involving control systems, protective logic, computer controlled functions and manual control.
- Post initiator interactions that involve procedure specified actions and recovery actions developed from training and experience.

5. Identify the best way whereby safety on board fishing vessels can be assured and develop a suitable model to assist in its implementation.

1.5.1 Scope of work

This thesis presents the work completed by the author for the duration of the research commencing in September 1998. It illustrates the findings of research carried out into FSA with reference to fishing vessels. The body of the report is divided into nine chapters. Each chapter is summarised here, highlighting the salient points delivered.

Chapter 2 highlights the international conventions that govern fishing vessel safety and some of the safety programmes that have been implemented by the International Maritime Organisation (IMO) member states. The findings from the literature review are discussed and where possible, graphs are generated to determine the trend in accidents. The data that was collected and analysed from various sources including the Department of the Environment, Transport and the Regions (DETR) and the Marine Accident and Investigation Branch (MAIB), are presented in the form of graphs, pie charts and tables to enable easy reading. The findings of the accident data gathered and the problems of lack or incomplete data to carry out fishing vessel safety assessment are discussed.

Chapter 3 describes the typical risk and safety assessment techniques that are available in the industry. The advantages and disadvantages of each method are reviewed. This is followed by a proposed approach to identifying hazards on fishing vessels using one of the typical methods described.

Chapter4 discusses the inception of FSA, starting from the disastrous Piper Alpha incident in 1988 and the consequent unfolding events, which led to the proposal by the Marine Coastguard Agency (MCA) to the IMO. The concept of FSA consists of five steps, which are the identification of hazards, assessment of the risks associated with those hazards, identification of ways of managing the risks, cost benefit assessment of the identified options determined and making decisions on which options to select. These five steps are briefly discussed, highlighting the interaction and continuity of

These classifications of human interactions can be related to a simple error classification system consisting of three categories: (1) slips, (2) non-response, and (3) mistakes. This classification scheme can then be used to qualitatively incorporate human errors in accident scenarios. Table 8.1 provides generic human error probabilities for use in accident scenario assessment [Department of Energy, 1996].

The development of a generic set of failure probabilities for human error is extremely difficult since there is a strong correlation on the actual person performing the task, complexity of the task, the time required for task completion, and the training level of the person performing the task. Additionally, a worker may perform any specific task differently depending on the level of alertness due to fatigue or other factors.

A relatively simple model has been developed by Rasmussen to quantify human error rates based on the level of training [Rasmussen J., 1979; Rasmussen J., 1981] This model divides the behaviour into three basic categories, skill-based, rule-based, and knowledge-based behaviours.

8.3.1 Skill-based

Skill-based behaviours depend mostly on the operator's practice in performing the task. In short the operator can perform the task without ambiguity. A simplistic view is that skill-based errors are slips or lapses. These errors tend to be related to highly routine activities in familiar circumstances: omissions, repetitions, reversals, interference errors and double-capture slips. For example, incorrect use of controls: fork-lift trucks have a number of different types of foot pedal controls. Some operate with three pedals (as a car), others have two pedals, reverse and forward. Removing a foot from either accelerator brings the vehicle to a halt. A common error is for the driver to press the backward accelerator in the belief (wrongly) that it is a brake pedal. Double-capture slips result from the influence of a recent highly practised routine on the task at hand. Examples of slips and lapses include:

- Failing to disengage the gears before starting the engine (omission).
- Turning the ignition key to start the engine, when the engine is already running (repetition).

- Pressing the brake instead of the accelerator (reversal).

8.3.2 Rule-based

Rule-based behaviour is at work when the operator does not have the same level of practice at performing the required task, but has a clear knowledge of the procedures. There may be some hesitation in recalling any procedure, the procedure may not be carried out in the proper sequence, or any step may not be performed precisely.

Rule-based errors are concerned with the misapplication or inappropriate use of problem solving rules. Individuals have a complex array of specific and general rules that they use to deal with everyday problems. Rules are of the type *if* <event> *then* <action>. Some simplistic examples relating to the operation of vehicles are:

- *if* <machine blockage> *then* <disengage power, switch off engine and investigate>
- *if* <pallet insecure> *then* <re-secure>
- *if* <towing a trailer on slopes> *then* <connect trailer brakes>

Sometimes the operators' rules are incomplete:

- *if* <emergency> *then* <apply handbrake, switch off engine, and dismount>

This is a perfectly good rule under most circumstances. However, with accidents involving contact with high voltage overhead lines, remaining in the cab provides protection against electrocution (principle of the Faraday Cage). A better additional rule would be:

- *if* <emergency involving electricity> *then* <stay in cab until supply isolated>.

The role of training in providing individuals with a set of safe rules is crucial.

8.3.3 Knowledge-based

Knowledge-based action would include situations where the operator needs to contemplate the situation, interpret information or make a difficult decision. Also included in this grouping would be cases where a procedure is not well spelled out. In these cases the person performing the task must consider the actions to be taken and not act according to specific training.

Knowledge-based errors are concerned with performance in novel or new situations. Actions have to be planned "on-line" and the process is intellectually demanding. The problem solver will only resort to this type of activity when they have run out of rule-based solutions. An example of knowledge-based performance is that of first learning to operate a piece of machinery. The hydraulic controls of a winch provide a good example. Experimentation will help the operator to build a mental model of how the controls can be co-ordinated to achieve the desired movements. Eventually, the operator will adopt a set of rules derived from that mental model. With practice, the task will become skill-based. Training offers the opportunity to miss out the experimentation phase by guiding the trainee to correct models of situations, based on the experiences of others.

Rasmussen provides per demand ranges and point estimates for these different categories [Rasmussen J., 1982]. These values are presented in table 8.2. Swain and Guttmann suggest for screening purposes, the values of 0.05 and 1 are used for the rule-based and knowledge-based actions respectively [Swain A. D. and Guttmann H. E., 1983]. However a value of 1 means 100% error rate for the knowledge-based action, a value that would appear to be unrealistically high.

One problem with the Rasmussen data is that it requires subjective analysis of the operator's training and capabilities. A set of human error rates were developed by Hunns for more specific tasks, not relying as much on the operator's capabilities and knowledge [Hunns D. M., 1982]. These data are presented in table 8.3 and were based on extrapolation from human error rate databases. These data are similar to the rates of Rasmussen, table 8.2, but provide some actual examples and do not require as much subjective analysis as the Rasmussen data.

Human Error Probability	**Description of human interaction and error**	**Example factors for a facility specific adjustment**
3×10^{-3} to 3×10^{-4}	Pre-Initiator actions - Test, maintenance, and calibrations leaving a component, or system with un-revealed fault. Includes typical errors in maintenance that cause overall system unavailability (10^{-3})	No written procedure available, or newly defined action; verbal instructions, no checking for completed action, poor equipment/procedure identification label matching.
	Errors include: slips, non-responses, or mistakes leading to skipping a procedure, selecting an incorrect procedure, omitting a step in a procedure, improper communication, transposition of labelling, or misunderstanding task responsibility.	Use established, practised, written procedures, discussed in training, work progress verified with signed checklist, apply self-checking, use tag-out system to maintain configuration control, etc.
1×10^{-2} to 1×10^{-4}	Initiator actions - Test, maintenance and calibration activities that trigger events. Include contribution of errors that cause initiating events - covered in initiating event frequencies (10^{-3})	Signals and instruments inappropriate for the action and procedure, lack of cues, or verbal instructions for interlocks, need for process knowledge, requires interpretation of indirect information, etc.
	Typical error modes include slips, non-responses and mistakes.	Indications permit easy transfer through procedures, discussed in training, practiced before hand, administrative control of tags, training involves understanding of the basic principles, and feedback of lessons learned from event precursors.
1 to 1×10^{-3}	Post-Initiator actions - Response actions that are not successful in terminating or mitigating the event. Includes recovery actions subsequent to initiating events: (.1) following multiple failures and (.03) directly following an initiating event.	Actions typically outside control room, involves more than one person, lack of a clear cue, knowledge of the process required, process knowledge substituted for emergency procedures, etc.
	Errors include slips, mistakes, and non-responses for control and mitigation actions following an initiating event.	Actions in a control room, include redundant cues, memorised and practised responses, clear man-machine interface, action priorities stressed in training which includes simulation of process dynamics, recoverability from errors, training on infield procedures and long time available for action.

Table 8.1 Generic human failure probabilities

	Per demand error rate range	Per demand error rate point estimate
Skill-based	5E-5 to 5E-3	1E-3
Rule-based	5E-4 to 5E-2	1E-2
Knowledge-based	5E-3 to 5E-1	1E-1

Table 8.2 Error rates of Rasmussen

Classification of error type	Typical probability
Processes involving creative thinking, unfamiliar operations where time is short; high stress situations	0.1-1
Errors of omission where dependence is placed on situation cues or memory	1E-2
Errors of commission such as operating wrong button, reading wrong dial, etc.	1E-3
Errors in regularly performed, common-place tasks	1E-4
Extraordinary errors - of the type difficult to conceive how they could occur; stress-free, powerful cues militating for success	<1E-5

Table 8.3 Error rates of Hunns

The human error rates for some specific tasks have been provided by Dhillon and are presented in table 8.4 [Dhillon B. S., 1986]. Dhillon points out that there are six basic categories of error sources that can eventually lead to an accident condition:

1. Operating errors
2. Assembly errors
3. Design errors
4. Inspection errors
5. Installation errors
6. Maintenance errors

Operating errors can be the result of:

1. Lack of proper procedures.
2. Task complexity and overload (of operator) conditions.
3. Poor personnel selection and training.
4. Operator carelessness and lack of interest.
5. Poor environmental conditions.
6. Departure from following correct operating procedures.

Error	Rate per demand	Rate per plant-month
Reading a chart recorder	6E-3	
Reading an analog meter	3E-3	
Reading graphs	1E-2	
Interpreting incorrectly an indicator	1E-3	
Turning a control in the wrong direction under high stress	0.5	
Using a checklist incorrectly	0.5	
Mating a connector	1E-2	
Choosing an incorrect panel control out of several similar controls	3E-3	
Reading a gauge incorrectly	5.0E-3	
Closing a valve improperly	1.8E-3	
Soldering connectors improperly	6.5E-3	
Actuating switch inappropriately	1.1E-3	
Failure to tighten nut and bolt	4.8E-3	
Failure to install nut and bolt	6E-4	
Improper adjustment of mechanical linkage	1.7E-2	
Procedural error in reading instructions	6.5E-2	
Connecting hose improperly	4.7E-3	
Failure to pursue proper procedure by an operator		0.040
Installation error		0.013
Misinterpretation or misunderstanding of requirements by the operator		0.0076
Inadvertent or improper equipment manipulation by the operator		0.071
Improper servicing or re-assembly by the maintenance personnel		0.015

Table 8.4 Error rates of Dhillon

8.4 Analytical Hierarchy Processing

Analytical Hierarchy Processing (AHP) is a powerful and flexible decision making process to help set priorities and make the best decision when both qualitative and quantitative aspects of a decision need to be considered. By reducing complex decisions to a series of one-on-one comparisons, then synthesising the results, AHP not only helps decision-makers arrive at the best decision, but also provides a clear rationale that it is the best. Designed to reflect the way people actually think, AHP was developed more than 20 years ago by Dr. Thomas Saaty, and continues to be the most highly regarded and widely used decision-making theory [Saaty T.L., 1980].

AHP is especially suitable for complex decisions, which involve the comparison of decision elements that are difficult to quantify. It is based on the assumption that when faced with a complex decision the natural human reaction is to cluster the decision elements according to their common characteristics. It involves building a hierarchy (ranking) of decision elements and then making comparisons between each possible pair in each cluster (as a matrix). This gives a weighting for each element within a cluster (or level of the hierarchy).

The AHP engages decision-makers in breaking down a decision into smaller parts, proceeding from the goal to criteria to sub-criteria down to the alternative courses of action. Decision-makers then make simple pair-wise comparison judgements throughout the hierarchy to arrive at overall priorities for the alternatives.

The literature survey on AHP indicates that the method has been effective to a wide range of applications. These include agricultural applications [Alho J.M. and Kangas J., 1997; Braunschweig T., 2000], industrial engineering applications [Alidi A.S., 1996; Bhattarai S. and Fujiwara O., 1997] and financial applications [Hachadorian G.E., 1987; Gerrits M. et. al., 1994]. The application of AHP theory to ascertain business and financial risk have been relatively popular in the past [Jensen R.E., 1987a; Jensen R.E. 1987b; Nezhad H.G., 1988; Simkin M.G. et. al., 1990]. It has also found its place in risk and safety assessment of engineering systems [Shields T.J. and Silcock G., 1986; Saaty T.L., 1987; Hamalainen R.P. and Karjalainen R., 1989; Shields T.J. et. al., 1990; Hamalainen R. P. and Karjalainen R., 1992; Frank M. V., 1995]

8.4.1 Principles and background of AHP

When considering a group of activities (factors) for evaluation, the main objectives of this group are [Saaty T.L., 1990]:

(1) To provide judgement on the relative importance of these activities.

(2) To insure that the judgements are quantified to an extent which also permits a quantitative interpretation of the judgement among these activities (factors).

The quantified judgement on pairs of activity c_i and c_j are represented by an n-by-n matrix.

$$A = (a_{ij}) \text{ where } ij = (1,2,3.......n) \qquad (1)$$

The entries a_{ij} are defined by the following entry rules:

Rule 1. If $a_{ij} = \alpha$, then $a_{ji} = 1/\alpha$, $\alpha \neq 0$.

Rule 2. If C_i is judged to be of equal relative importance as C_j, then $a_{ij} = a_{ji} = 1$.

Obviously $a_{ii} = 1$ for all i. Thus the matrix A has the following form:

$$A = \begin{bmatrix} 1 & a_{12} & \ldots\ldots & a_{1n} \\ 1/a_{12} & 1 & \ldots\ldots & a_{2n} \\ . & . & \ldots\ldots & . \\ 1/a_{1n} & 1/a_{2n} & \ldots\ldots & 1 \end{bmatrix} \qquad (2)$$

where the a_{ij} is the relative importance of activity i to activity j. Having recorded the quantified judgements of comparisons on pairs $(C_i$, C_j) as numerical entries a_{ij} in the matrix A, what is left is to assign to the n contingencies C_1 , C_2 , C_3 , ... C_n a set of numerical *weights* w_1 , w_2 , w_3 , ..., w_n that should reflect the recorded judgements. The eigenvector of the comparison matrix provides the priority ordering (weight), and the eigenvalue is a measure of consistency. To find the priority vector or the weight of each factor included in the priority ranking analysis, the eigenvector corresponding to the maximum eigenvalue is to be determined from matrix analysis. One of the approximation methods to get the weight of each factor in the pair-wise comparison process is described below.

8.4.2 Weight vector calculation

In mathematical terms, the principal eigenvector is computed, and when normalised becomes the vector of priorities (weights). To reduce the excessive computing time needed to solve the problem exactly, and due to the results of complex numbers, a good estimate of that vector can be obtained by dividing the elements of each column in the comparison matrix by the sum of that column (i.e. normalise the column). The elements in each resulting row are added and the sum is divided by the number of the elements in the row. This is a process of averaging over the normalised columns. Mathematically, this process is shown below:

$$W_1 = \frac{1}{n}\left[\left(\frac{a_{11}}{\sum_i a_{i1}}\right) + \left(\frac{a_{12}}{\sum_i a_{i2}}\right) + \ldots . \left(\frac{a_{1n}}{\sum_j a_{in}}\right)\right] \quad (3)$$

or in general

$$W_1 = \frac{1}{n}\sum_j \left[\left(\frac{a_{ij}}{\sum_i a_{ij}}\right)\right] \quad (4)$$

where a_{ij} is the entry of row i and column j in a comparison matrix of order n.

8.4.3 Risk and AHP

Risks are by nature subjective, therefore, to analyse their potential of contributing to a failure, the AHP method is used. This technique allows subjective and objective factors to be considered in risk analysis and also provides a flexible and easily understood way to annualise subjective risk factors. The elements in each level are compared pair-wise with respect to their importance in making the decision under consideration. The verbal scale used in AHP enables the decision-maker to incorporate subjectivity, experience and knowledge in an intuitive and natural way.

After the comparison matrices have been created, the process moves on to the phase in which relative weights are derived for the various elements. The relative weights of the elements of each level with respect to an element in the adjacent upper level are computed as the components of the normalised eigenvector associated with the largest eigenvalue of their comparison matrix. The composite weights of the decision alternatives are then determined by aggregating the weights through the hierarchy. This is done by following a path from the top of the hierarchy to each alternative at the lowest level, and multiplying the weights along each segment of the path. The outcome of this aggregation is a normalised vector of the overall weights of the options. The mathematical basis for determining the weights has been established by Saaty [Saaty, T.L., 1980].

8.4.4 AHP for human error assessment and decision making for fishing vessels

Several methods to quantify human error probability have been reviewed in section 8.2. These methods suffer from the difficulty associated with any attempt to construct quantitative, predictive models of human behaviour. The qualitative methods on the other hand, require multi-disciplinary teams to carry out an analysis and this is regarded as being resource intensive. The more recent HRA methods have included cognitive aspects of decision making and the "time" dimension. However, it has not yet captured the fundamental nature of the interaction between actions and machine responses [Cacciabue P.C. et. al., 1993] These interactions lie in the mutual dynamic influence of the operator, the plant and the interfaces.

The use of AHP to evaluate human error on fishing vessels does not ignore small events or operations that are normally rationalised and eliminated as being not important in traditional methods. A chain of these small rationalisations results in a larger problem later. The AHP method looks at every event/operation and ranks them against each other to determine the importance of each event/operation over the other (without eliminating them from the analysis).

The use of the AHP method enables the solutions for each possible human error identified, to be integrated within the analysis. This is unlike the methods reviewed in section 8.2, where the solutions to reduce the risk levels (posed by human errors) are evaluated in the first instance, and then a re-iteration of the whole analysis is performed (assuming the implementation of the solution) to confirm the risk reduction. A proposed approach using the AHP method for human error assessment and decision making applied to fishing vessels is presented in section 8.5.

8.5 A Proposed Approach for Fishing Vessels

The flowchart in figure 8.1 illustrates the steps involved in carrying out the proposed approach. This approach can be executed in seven distinct steps:

each step (as proposed by the MCA). The result from one step of the process is linked to the next to ensure that no information is lost and the analysis is comprehensive. Reiteration within the FSA process is expressed by means of a flowchart. The breakdown of individual tasks within the five steps is explained and the accompanying risk assessment tools used are listed and their use within the FSA process is described. A general framework for the application of the FSA to generic fishing vessel is proposed and is demonstrated using a test case. The findings of this test case and the use of novel techniques to improve the FSA framework as applied to fishing vessels are discussed.

Chapter 5 proposes a new approach to modelling the probability of occurrence of a hazard and its severity using Fuzzy Set Theory (FST) with Fault Tree Analysis (FTA). The literature survey indicates that the common problem in quantifying these parameters (of an event failure) is often the small sample size and the statistical uncertainties, which are correspondingly high. The new proposed approach utilises FST and expert judgements to deal with this high level of uncertainty. It involves the generation of a fault tree of known events and its synthesis with fuzzy arithmetic to produce a linguistic term for the top event (an undesirable event). Linguistic terms such as *Very High, High, Moderate, Low* and *Remote* are used. Mathematical formulas used for calculations in the fault tree are derived from the theory of probability and integrated with fuzzy arithmetic on α-cut sets. A score ranking system is proposed where each failure event is evaluated for its effect on four different categories, which are the personnel, environment, equipment and catch category. The output of the proposed approach is in the form of a crisp number, which reflects the risk ranking of the event failure. A trial application of the proposed approach is carried out on a winch operating system of a fishing vessel. The results obtained from the analysis will prove useful to fishing vessel owners and operator as the time, effort and money spent on systems within a ship can be justly proportioned.

Chapter 6 proposes a new modified approach to Failure Mode and Effects Analysis (FMEA) which incorporates the use of fuzzy rule base and grey theory. The traditional method utilises the Risk Priority Number (RPN) ranking system. This method

1. Describe system - The system or operation under consideration is described in detail, highlighting all the equipment within the system that will be operated to achieve the desired objective of the defined operation.
2. Identify tasks to be carried out - Identify all tasks that are to be carried out to achieve the objective of the operation and present these tasks in the order that they should be carried out. This information can be represented by means of a flow chart. The order by which the tasks are carried out should reflect the normal safe working procedure of the system. To enable effective use of this information in the AHP phase, all tasks are annotated according to the equipment that are operated.
3. Determine operator behaviour - For each of the task identified in step 2, determine the required operators behaviour. Three types of behaviours are considered namely, skill-based, rule-based or knowledge-based behaviour. These behaviours are discussed in sections 8.3.1, 8.3.2 and 8.3.3 respectively.
4. Determine the probability of occurrence - Using a generic database, determine the probability that a human error might occur while carrying out the task specified in step 2. Use the information developed in step 3 to assign the probability of occurrence of the human error.
5. Determine the severity of occurrence - The severity of a human error should take into account the consequences of the error on the system, operation, environment and operator. This can be quantified in monetary terms or downtime.
6. Determine Risk Control Options (RCO) - Considering the system/operation under study; determine several options that could address the risks identified (associated with each task defined in step 2). The RCOs proposed should be carefully thought through and be feasible for implementation within the system/operation studied.
7. AHP analysis - Using the data gathered in steps 2, 4, 5 and 6, carry out the AHP analysis to determine the most favourable RCO. This RCO will address all the risks associated with tasks where human errors could manifest.

Step 7 (AHP analysis) involves 4 distinct steps, which are described here:

a) Set-up - Decision making criteria are generated, often by brainstorming or past experience. Hierarchical relationships are drawn between the criteria and are then represented in a matrix form.

b) Weighting - The matrices are filled with the criteria comparisons. The comparisons allow calculation of the criteria-weighting vector.

c) Ranking - The different RCOs are ranked on their ability to satisfy the various criteria.

d) Evaluation - The final solution ratings are then calculated using the ratings determined in step (c) and the weighting vector calculated in step (b).

The first task is to decide on the problem statement. This statement becomes Level One or the goal of the hierarchy and will be broken down into nested levels (Level Two). Level Two will comprise of the different elements needed to be considered to achieve the goal set in the problem statement. The elements in Level Two is further broken-down to represents the various constituents that make up or belong to each specific element. The hierarchical structure is assumed to exist inherently in the problem considered and can be identified.

The hierarchy records the flow of detail from the problem statement (Goal) to broad issues (Level Two) and more specific levels (Level Three). While the concerns on a particular level are not equally important, they should be on the same order of magnitude. This feature in AHP allows decisions to be made involving different orders of magnitude criteria, by placing each criterion in its proper matrix in the objective hierarchy. Figure 8.2 shows an example of the hierarchy represented diagrammatically.

Once the hierarchy has been completed, matrices are constructed with the criteria labels on each axis. There will be one Level Two matrix and one matrix containing the sub-elements of each element. For example, the sample in figure 8.2 will have one Level Two matrix and three Level Three matrices. These Level Three matrices may be broken down in finer detail where applicable. The two axes of the matrix will contain the names of the elements on the level being considered. For example, the Level Two matrix in figure 8.2 will have the form shown in figure 8.3. The levels below each of the Level Two elements would also be represented in a matrix form. Figure 8.4 shows an example for the Element 1 (constituent A) matrix. The complete representation of Element 1 would comprise of three matrices (as Element 1 has the constituents A, B and C).

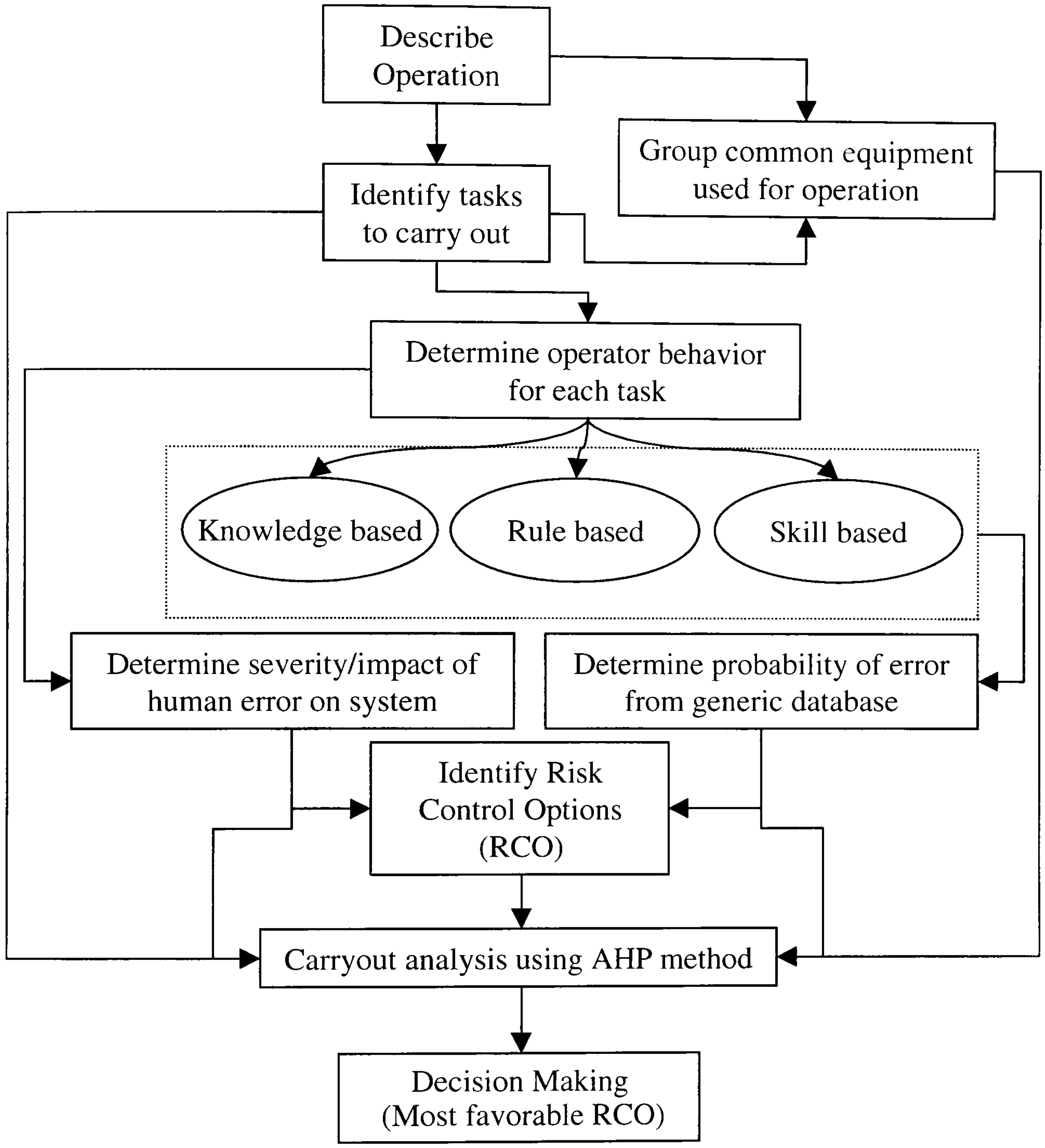

Figure 8.1 Flowchart of the proposed approach

As the proposed method does not use historical data (probability of occurrence in terms of hard numbers or severity in terms of number of deaths), the uncertainty in these parameters are captured by representing them in terms of preference/importance against each other. Hence, the analysis is targeted at improving the current situation by identifying the areas that need improving, rather than trying to quantify the occurrence of an undesired event.

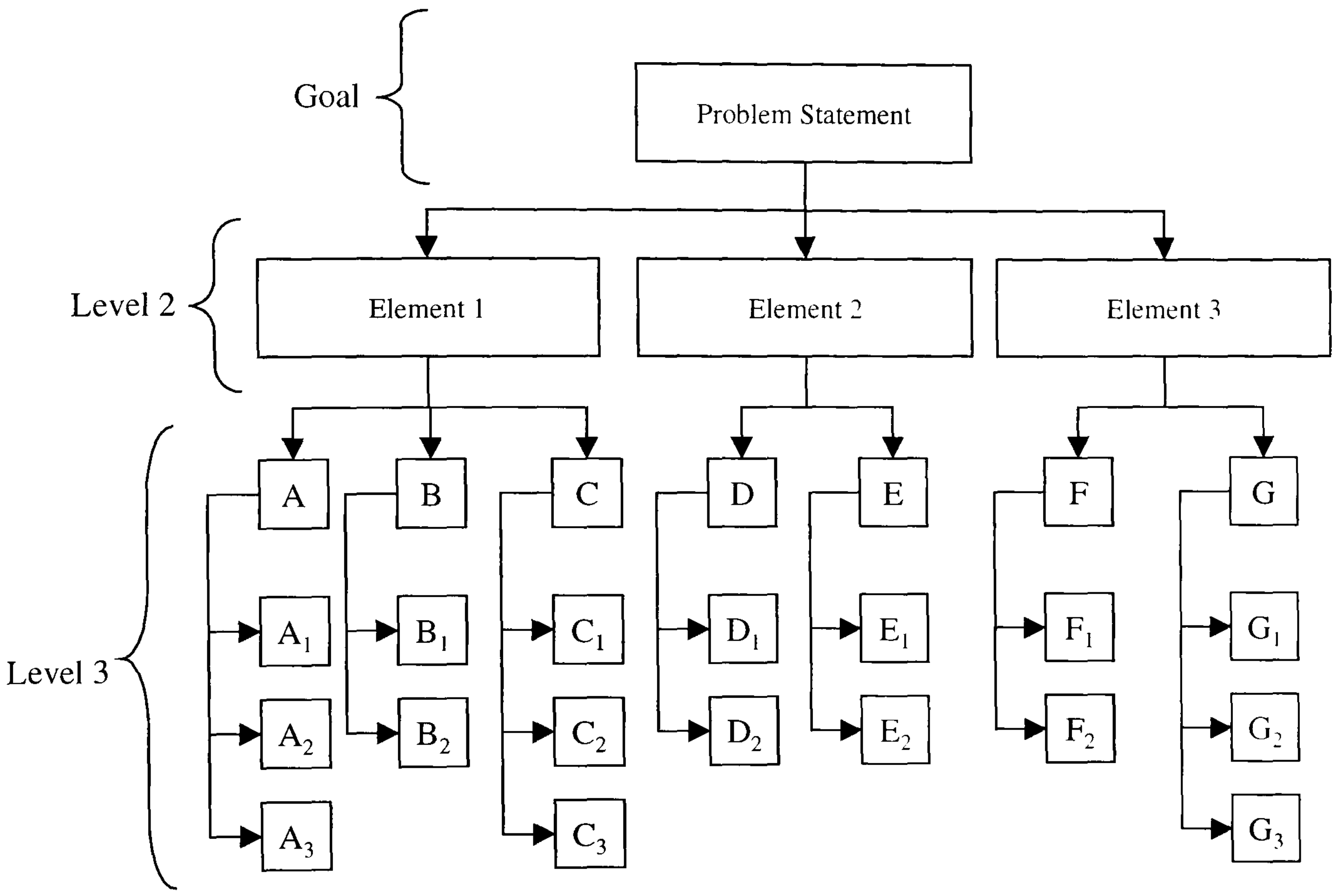

Figure 8.2 Example of hierarchy levels

Level Two	Element 1	Element 2	Element 3
Element 1	EL_{11}	EL_{12}	EL_{13}
Element 2	EL_{21}	EL_{22}	EL_{23}
Element 3	EL_{31}	EL_{32}	EL_{33}

Figure 8.3 Example of Level Two matrix

Element 1	A_1	A_2	A_3
A_1	A_{11}	A_{12}	A_{13}
A_2	A_{21}	A_{22}	A_{23}
A_3	A_{31}	A_{32}	A_{33}

Figure 8.4 Example of Level Three matrix

Upon generating the matrices for all the elements, it must now be filled with the comparisons of the relative importance of the elements on the two axes. The comparisons are used to calculate the weighting vector that will give the relative importance of all the elements. The entire weighting vector is calculated from comparisons made between just two elements at a time. Table 8.5 shows the scale (1 to 9) proposed by [Saaty T.L, 1980] for indicating the relative importance between the elements.

1	Both elements of equal importance
3	Left weakly more important than top
5	Left moderately more important than top
7	Left strongly more important than top
9	Left absolutely more important than top

1/3	Top weakly more important than left
1/5	Top moderately more important than left
1/7	Top strongly more important than left
1/9	Top absolutely more important than left

Table 8.5 Comparison scale

Considering the example of the Level Two matrix in figure 8.3, and assuming that Element 1 is weekly more important than Element 2 and strongly more important than Element 3. Then, the matrix in figure 8.3 may be represented as seen in the matrix below:

$$Level\ Two = \begin{bmatrix} 1 & 3 & 7 \\ 1/3 & 1 & 7/3 \\ 1/7 & 3/7 & 1 \end{bmatrix}$$

In the matrix, Element 1 is of equal importance with respect to itself, so 1 is placed in the upper left-hand corner. A consistent matrix formulation allows the remainder of the matrix to be completed given the information in the top row. Since the relationship is known between Element 1 and Element 2, and Element 1 and Element 3, the relationship between Element 2 and Element 3 can be determined. In this case the matrix entry for Element 2 versus Element 3 would contain 7/3. Similarly, the rest of the matrix can be computed using the formula $a_{ij} = a_{1k} / a_{1j}$.

The weighting vector is then determined to give the percentage of the total weight applied to each element. The first column in the Level Two matrix, (1, 1/3, 1/7) is normalised so that the sum of the entries is 1.0. The weighting vector of Element 1 will be given as 1/(1+1/3+1/7) = 0.667 or 67.8%. Similarly Elements 2 and 3 can be calculated to be 22.6% and 9.68%. The sum of all three weighting vectors should be equal to 100%.

The comparison process is repeated for all the matrices to be used in the analysis. The weighting vectors of the lower matrices will be normalised by the weight associated to the sub-elements' matrix, so that their total weight will equal that of the previous level (Level Two). For example, for Element 1 sub-element A_1, A_2, A_3, B_1, B_2, C_1, C_2 and C_3 will be given a total weight of 67.8%. All sub-elements are analysed in the same fashion to the lowest level possible and the results are normalised to reflect the weight of each sub-element in the hierarchy.

The next step is to generate the possible solution to achieve the problem statement/goal. Each solution is compared against each of the lowest level sub-elements. The possible solutions are assumed to reduce the likelihood of human error occurring and/or the possible consequences. The evaluation represents the "effectiveness" of the solution in controlling the risks. These evaluations (of the solutions) are recorded with a user defined numerical scale, as appropriate for the sub-elements. For any given element, a normalised score is determined for each solution by taking the assigned score (which may have units) and dividing it by the sum of the assigned scores across all of the solutions. This fraction is then multiplied by the weighting coefficient for the element. This will give a normalised score for each solution based on the element considered. These normalised results are then summed down the different elements in the matrix, to arrive at a final rating for each solution. The result of this series of operations is a weighted rating for each solution. The highest rated solution will best meet the problem statement (goal).

8.6 An Example

The purpose of this analysis is to address the high level of human errors that occur during the fishing operation on board fishing vessels. As an example, the initial shooting operation of the fishing nets is considered.

8.6.1 Initial shooting operation

At the commencement of the voyage the beams are stowed port and starboard alongside and inboard of the bulwark rails. The cod ends are held by the Gilson wires up at the cod end lifting blocks with the netting hanging down to the chain mat that is beneath the beam. As soon as the vessel clears the harbour, the derricks are lowered to an angle of approximately 45 degrees. This reduces the top weight on the vessel, improving stability but importantly, it is to prevent the derricks from moving past vertical and falling inboard as the vessel rolls.

On reaching the fishing grounds, the vessel stops and, working one side at a time, the derrick is raised sufficient to lift the beam and chain mat up and over the rail, the derrick being lowered back to 45 degrees on completion of the manoeuvre. While the cod ends are held by Gilson wire over the lifting block, the netting is paid overboard.

Attached between the inboard end of the beam and the cod end lifting becket is a heavy rope, referred to as a 'lazy decky'. This rope is pulled to swing the beam around to bring it normal to the vessel side. The vessel moves ahead slowly and the Gilson wires are lowered slightly, sufficient to allow the cod ends to be swung over the rail: but still with the Gilson hooks attached in the lifting becket, the weight being carried by the cod ends lifting blocks. The crew, on each side, then takes the 'lazy decky' and makes it fast on a bulwark rail pin such that the weight of cod end is carried by the pin. The remainder of the 'lazy decky' lies in a bight on the deck up to the point where it goes over the rail to hang in a bight between the vessel and the beam. Once the weight of the cod end has been transferred to the rail pins, the Gilson hooks are released, the derricks are lowered fully outboard, and the vessel is brought up to speed. When the crew in the wheelhouse, either the skipper or the mate, is satisfied that the vessel is running straight and true, he signals to the crewman to release the 'lazy decky' ropes from the rail pins. The cod ends then stream astern with the netting stretched out. Warp is then paid out, typically 200 fathom for sea depth of 40 fathom. Due to the double purchase around the block on the beam, 200 fathoms of warp is in effect a 100 fathom pay-out giving a typical warp/depth ratio of 2.5:1. The complete initial shooting operation can be represented diagrammatically as seen in figure 8.5.

8.6.2 Hierarchy set-up

The various tasks identified above are used to set up the hierarchy of elements. The goal of the analysis is determined to be the safe initial shooting operation. The elements in Level Two is set to be the probability of a human error occurring and the severity of human error. The sub-elements (Level Three) are determined by grouping the equipment that are operated i.e. derrick, vessel, lazy decky, net and Gilson. Each task carried out in relation to these equipment is considered within this level i.e. derrick 1, derrick 2, derrick 3, etc. The hierarchy can be represented diagrammatically as seen in figure 8.6.

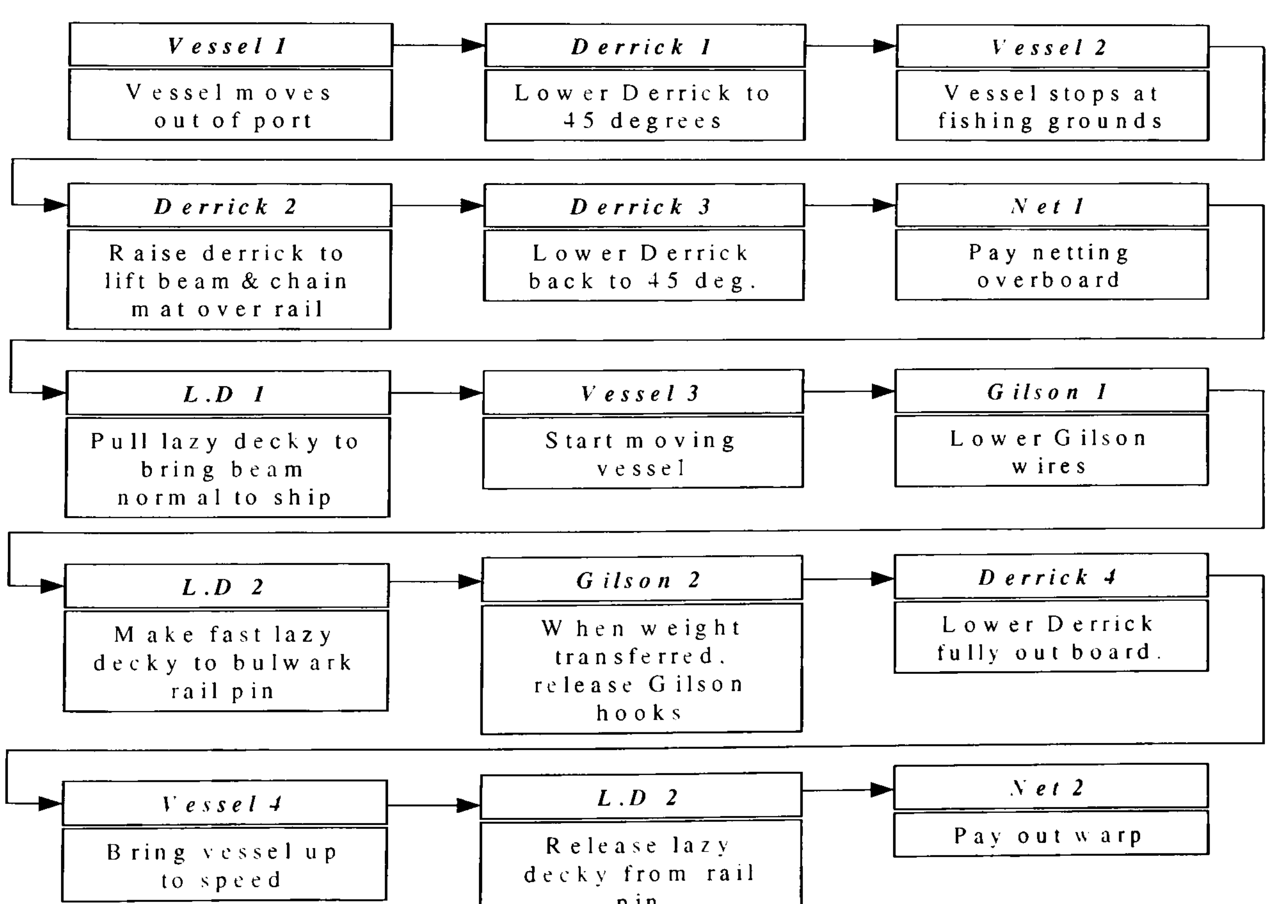

Figure 8.5 Diagrammatic representation of initial shooting operation

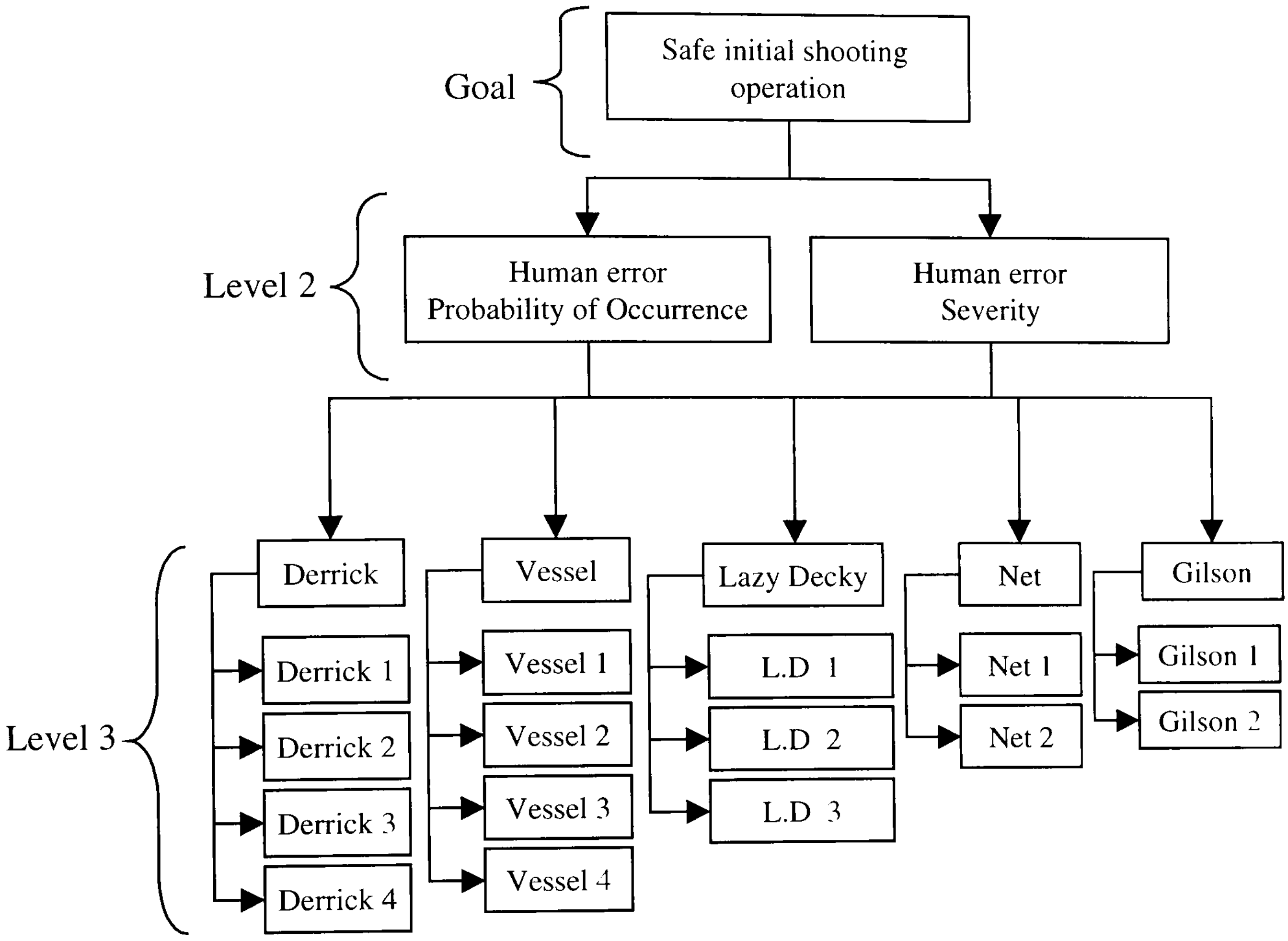

Figure 8.6 Initial shooting operation hierarchy levels

8.6.3 Level Two matrix

The probability of occurrence and severity make up the two elements in Level Two as seen in figure 8.6. These two elements are compared against each other to determine the weighting vector of each element. The comparison scale in table 8.5 is used to determine the importance of the two elements. Considering the goal of the analysis, it is decided that both these elements are equally important to a safety assessment, hence, the Level Two matrix is determined as:

$$Level\,Two = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}, \text{ and the } Weighting\,Vector = \begin{bmatrix} 0.5 \\ 0.5 \end{bmatrix}$$

8.6.4 Human error probability evaluation

First, the importance of each element (derrick, vessel, lazy decky, net and Gilson) is determined. Using the comparison scale in table 8.5, the matrix below is obtained for the probability importance of each element.

$$\textbf{Probability} = \begin{bmatrix} 1.00 & 7.00 & 3.00 & 9.00 & 5.00 \\ 0.14 & 1.00 & 0.43 & 1.29 & 0.71 \\ 0.33 & 2.33 & 1.00 & 3.00 & 1.67 \\ 0.11 & 0.78 & 0.33 & 1.00 & 0.56 \\ 0.20 & 1.40 & 0.60 & 1.81 & 1.00 \end{bmatrix}$$

The weighting vector and normalised vector is determined by considering the weighting vector obtained in the Level Two matrix and is shown here:

$$\textit{Weighting Vector} = \begin{bmatrix} 0.5595 \\ 0.0799 \\ 0.1865 \\ 0.0622 \\ 0.1119 \end{bmatrix} \text{ and } \textit{Normalised Vector} = \begin{bmatrix} 0.2798 \\ 0.040 \\ 0.0933 \\ 0.0311 \\ 0.0560 \end{bmatrix}$$

The probability of human error is considered for each of the task carried out by determining the type of human behaviour required to carry out the task successfully. Using the generic human error data by Rasmussen (table 8.2), each task is assigned operator behaviour and the generic error probability. This data is then used to compare each task against the others to determine the Level Three matrix. The various tasks identified in this example and the associated generic data is provided in table 8.6.

determines the RPN by finding the multiplication of factor scores. The three factors considered are the probability of failure, severity and detectability. Traditional FMEA has been criticised to have several drawbacks. These drawbacks are reviewed and are addressed in the proposed approach. The purpose of the new approach is to utilise expert judgement in a formal method to produce a more accurate and logical ranking of the failure events identified during the hazard identification phase. It also allows for the analyst to assign weighting factors to the decision criteria in order to identify where improvements can be made to the system. A test case is presented using the modified FMEA proposed. The potential of integrating the modified FMEA to the FSA process is discussed.

Chapter 7 identifies the areas that require improvement on fishing vessels. The results obtained from the data analysis in chapter 2 show that the failures could have been avoided if a proper maintenance regime was in place. The current maintenance strategies on fishing vessels are critically reviewed. Upon analysing the present situation of the industry, it is proposed that an inspection regime be implemented to arrest failures before they develop into catastrophic ones. A method employing delay-time analysis is proposed to determine the optimal inspection time. Three criteria are modelled, namely, downtime, cost and safety criticality. Based on the criterion selected, an optimum inspection time is obtained. A best compromise is also proposed where all three criteria are simultaneously minimised to acceptable levels. The proposed method is demonstrated on a winch operating system of a fishing vessel. The effect of the integration of an inspection regime within the current maintenance practice is studied and its advantages are highlighted.

Chapter 8 proposes a framework for the identification and quantification of human error in fishing vessel operation. This framework ranks the impact of human error and further integrates the available risk control options into the analysis. The method uses Analytical Hierarchy Processing (AHP) theory to rank the preference of each control option. A brief review of human error assessment techniques is presented discussing the requirements and characteristics of each technique. The advantages of employing the

Task	Operator behaviour	Error Probability
Derrick 1	Skill base	5.00E-03
Derrick 2	Skill base	5.00E-03
Derrick 3	Skill base	5.00E-03
Derrick 4	Knowledge base	5.00E-01
Vessel 1	Knowledge base	5.00E-01
Vessel 2	Rule base	5.00E-02
Vessel 3	Knowledge base	5.00E-01
Vessel 4	Skill base	5.00E-03
L.D 1	Skill base	5.00E-03
L.D 2	Skill base	5.00E-03
L.D 3	Skill base	5.00E-03
Net 1	Skill base	5.00E-03
Net 2	Skill base	5.00E-03
Gilson 1	Rule base	5.00E-02
Gilson 2	Knowledge base	5.00E-01

Table 8.6 Identified task and generic human error data

The matrices for the probability of occurrence for each task are determined as follows:

$$Derrick = \begin{bmatrix} 1.00 & 1.00 & 1.00 & 0.11 \\ 1.00 & 1.00 & 1.00 & 0.11 \\ 1.00 & 1.00 & 1.00 & 0.11 \\ 9.00 & 9.00 & 9.00 & 1.00 \end{bmatrix},$$

$$Weighting\ Vector = \begin{bmatrix} 0.0833 \\ 0.0833 \\ 0.0833 \\ 0.7500 \end{bmatrix}, \ Normalised\ Vector = \begin{bmatrix} 0.0233 \\ 0.0233 \\ 0.0233 \\ 0.2098 \end{bmatrix}$$

$$Vessel = \begin{bmatrix} 1.00 & 5.00 & 1.00 & 9.00 \\ 0.20 & 1.00 & 0.20 & 1.80 \\ 1.00 & 5.00 & 1.00 & 9.00 \\ 0.11 & 0.56 & 0.11 & 1.00 \end{bmatrix},$$

$$Weighting\ Vector = \begin{bmatrix} 0.4327 \\ 0.0865 \\ 0.4327 \\ 0.0481 \end{bmatrix},\ Normalised\ Vector = \begin{bmatrix} 0.0173 \\ 0.0035 \\ 0.0173 \\ 0.0019 \end{bmatrix}$$

$$Lazy\ Decky = \begin{bmatrix} 1.00 & 1.00 & 1.00 \\ 1.00 & 1.00 & 1.00 \\ 1.00 & 1.00 & 1.00 \end{bmatrix}$$

$$Weighting\ Vector = \begin{bmatrix} 0.3333 \\ 0.3333 \\ 0.3333 \end{bmatrix},\ Normalised\ Vector = \begin{bmatrix} 0.0311 \\ 0.0311 \\ 0.0311 \end{bmatrix}$$

$$Net = \begin{bmatrix} 1.00 & 1.00 \\ 1.00 & 1.00 \end{bmatrix}$$

$$Weighting\ Vector = \begin{bmatrix} 0.50 \\ 0.50 \end{bmatrix},\ Normalised\ Vector = \begin{bmatrix} 0.0155 \\ 0.1155 \end{bmatrix}$$

$$Gilson = \begin{bmatrix} 1.00 & 0.20 \\ 5.00 & 1.00 \end{bmatrix}$$

$$Weighting\ Vector = \begin{bmatrix} 0.1667 \\ 0.8333 \end{bmatrix},\ Normalised\ Vector = \begin{bmatrix} 0.0093 \\ 0.0466 \end{bmatrix}$$

8.6.5 Human error severity evaluation

The importance of each element (derrick, vessel, lazy decky, net and Gilson) is determined using the comparison scale in table 8.5, the matrix below is obtained for the severity importance of each element.

$$Severity = \begin{bmatrix} 1.00 & 7.00 & 3.00 & 9.00 & 5.00 \\ 0.14 & 1.00 & 0.43 & 1.29 & 0.71 \\ 0.33 & 2.33 & 1.00 & 3.00 & 1.67 \\ 0.11 & 0.78 & 0.33 & 1.00 & 0.56 \\ 0.20 & 1.40 & 0.60 & 1.81 & 1.00 \end{bmatrix}$$

The weighting vector and normalised vector is determined by considering the weighting vector obtained in the Level Two matrix and is shown here:

$$Weighting\,Vector = \begin{bmatrix} 0.5595 \\ 0.0799 \\ 0.1865 \\ 0.0622 \\ 0.1119 \end{bmatrix} \text{ and } Normalised\,Vector = \begin{bmatrix} 0.2798 \\ 0.0400 \\ 0.0933 \\ 0.0311 \\ 0.0560 \end{bmatrix}$$

The matrices for the severity of the consequences of human error for each task is determined as follows:

$$Derrick = \begin{bmatrix} 1.00 & 7.00 & 3.00 & 5.00 \\ 0.14 & 1.00 & 0.43 & 0.71 \\ 0.33 & 2.33 & 1.00 & 1.67 \\ 0.20 & 1.40 & 0.60 & 1.00 \end{bmatrix},$$

$$Weighting\,Vector = \begin{bmatrix} 0.5966 \\ 0.0852 \\ 0.1989 \\ 0.1193 \end{bmatrix}, \; Normalised\,Vector = \begin{bmatrix} 0.1669 \\ 0.0238 \\ 0.0556 \\ 0.0334 \end{bmatrix}$$

$$Vessel = \begin{bmatrix} 1.00 & 0.20 & 0.33 & 0.11 \\ 5.00 & 1.00 & 1.67 & 0.56 \\ 3.00 & 0.60 & 1.00 & 0.33 \\ 9.00 & 1.80 & 3.00 & 1.00 \end{bmatrix},$$

$$Weighting\ Vector = \begin{bmatrix} 0.0556 \\ 0.2778 \\ 0.1667 \\ 0.5000 \end{bmatrix},\ Normalised\ Vector = \begin{bmatrix} 0.0022 \\ 0.0111 \\ 0.0067 \\ 0.0200 \end{bmatrix}$$

$$Lazy\ Decky = \begin{bmatrix} 1.00 & 0.11 & 0.33 \\ 9.00 & 1.00 & 3.00 \\ 3.00 & 0.33 & 1.00 \end{bmatrix}$$

$$Weighting\ Vector = \begin{bmatrix} 0.0769 \\ 0.6923 \\ 0.2308 \end{bmatrix},\ Normalised\ Vector = \begin{bmatrix} 0.0072 \\ 0.0646 \\ 0.0215 \end{bmatrix}$$

$$Net = \begin{bmatrix} 1.00 & 5.00 \\ 0.20 & 1.00 \end{bmatrix}$$

$$Weighting\ Vector = \begin{bmatrix} 0.8333 \\ 0.1667 \end{bmatrix},\ Normalised\ Vector = \begin{bmatrix} 0.0259 \\ 0.0052 \end{bmatrix}$$

$$Gilson = \begin{bmatrix} 1.00 & 0.11 \\ 9.00 & 1.00 \end{bmatrix}$$

$$Weighting\ Vector = \begin{bmatrix} 0.1000 \\ 0.9000 \end{bmatrix},\ Normalised\ Vector = \begin{bmatrix} 0.0056 \\ 0.0504 \end{bmatrix}$$

8.6.6 Risk Control Options (RCO)

Several viable Risk Control Options (RCO) are generated in order to reduce the level of risks posed by human errors during the initial shooting operation. These risk control options are evaluated for their effectiveness against each of the operator tasks identified. For this example, an arbitrary scale (1 to 10) is used to compare each RCO, 1 being not effective and 10 being most effective. When assigning a score on the 1 to 10 scale, several factors are considered, such as, cost, ease of implementation, efficiency, time before solution becomes effective, etc. Six RCOs' have been identified to reduce the probability and severity of human errors of the initial shooting operation. These RCOs include:

RCO 1 - Training of crew
RCO 2 - Redesign system
RCO 3 - Incorporate additional interlocks
RCO 4 - Change operating procedures
RCO 5 - Additional crewing
RCO 6 - Install warning devices (audio and visual alarms, indications etc.)

The matrices for the effectiveness of each RCO in reducing the probability of occurrence are presented in the form as seen in figure 8.7. Similarly all tasks are compared with the different RCOs and their values normalised.

Derrick	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5	RCO 6
Derrick 1						
Derrick 2						
Derrick 3						
Derrick 4						

Figure 8.7 RCO matrix

8.6.7 RCO evaluation to reduce probability of occurrence

$$Derrick = \begin{bmatrix} 6 & 1 & 7 & 3 & 4 & 9 \\ 6 & 2 & 8 & 5 & 1 & 7 \\ 6 & 1 & 7 & 3 & 4 & 9 \\ 6 & 6 & 9 & 7 & 1 & 9 \end{bmatrix},$$

$$Normalised\ results = \begin{bmatrix} 0.0047 & 0.0008 & 0.0054 & 0.0023 & 0.0031 & 0.0070 \\ 0.0048 & 0.0016 & 0.0064 & 0.0040 & 0.0008 & 0.0056 \\ 0.0047 & 0.0008 & 0.0054 & 0.0023 & 0.0031 & 0.0070 \\ 0.0331 & 0.0331 & 0.0497 & 0.0386 & 0.0055 & 0.0497 \end{bmatrix}$$

$$Vessel = \begin{bmatrix} 8 & 1 & 3 & 2 & 4 & 7 \\ 7 & 1 & 2 & 2 & 4 & 7 \\ 7 & 1 & 3 & 2 & 4 & 7 \\ 9 & 5 & 3 & 2 & 6 & 8 \end{bmatrix},$$

$$Normalised\ results = \begin{bmatrix} 0.0055 & 0.0007 & 0.0021 & 0.0014 & 0.0028 & 0.0048 \\ 0.0011 & 0.0002 & 0.0003 & 0.0003 & 0.0006 & 0.0011 \\ 0.0050 & 0.0007 & 0.0022 & 0.0014 & 0.0029 & 0.0050 \\ 0.0005 & 0.0003 & 0.0002 & 0.0001 & 0.0003 & 0.0005 \end{bmatrix}$$

$$Lazy\ Decky = \begin{bmatrix} 4 & 3 & 7 & 2 & 6 & 9 \\ 5 & 2 & 8 & 3 & 6 & 8 \\ 6 & 4 & 8 & 3 & 7 & 8 \end{bmatrix}$$

$$Normalised\ results = \begin{bmatrix} 0.0040 & 0.0030 & 0.0070 & 0.0020 & 0.0060 & 0.0090 \\ 0.0049 & 0.0019 & 0.0078 & 0.0029 & 0.0058 & 0.0078 \\ 0.0052 & 0.0035 & 0.0069 & 0.0026 & 0.0060 & 0.0069 \end{bmatrix}$$

$$Net = \begin{bmatrix} 2 & 2 & 8 & 3 & 4 & 10 \\ 3 & 3 & 7 & 3 & 4 & 10 \end{bmatrix}$$

$$Normalised\ results = \begin{bmatrix} 0.0011 & 0.0011 & 0.0043 & 0.0016 & 0.0021 & 0.0054 \\ 0.0016 & 0.0016 & 0.0036 & 0.0016 & 0.0021 & 0.0052 \end{bmatrix}$$

$$Gilson = \begin{bmatrix} 5 & 3 & 6 & 5 & 6 & 7 \\ 7 & 3 & 10 & 6 & 6 & 10 \end{bmatrix}$$

$$Normalised\ results = \begin{bmatrix} 0.0015 & 0.0009 & 0.0017 & 0.0015 & 0.0017 & 0.0020 \\ 0.0078 & 0.0033 & 0.0111 & 0.0067 & 0.0067 & 0.0111 \end{bmatrix}$$

8.6.8 RCO evaluation to reduce severity of occurrence

$$Derrick = \begin{bmatrix} 6 & 1 & 5 & 5 & 4 & 7 \\ 6 & 2 & 7 & 5 & 4 & 7 \\ 6 & 1 & 5 & 6 & 4 & 7 \\ 6 & 4 & 6 & 7 & 5 & 9 \end{bmatrix},$$

$$Normalised\ results = \begin{bmatrix} 0.0358 & 0.0060 & 0.0298 & 0.0298 & 0.0238 & 0.0417 \\ 0.0046 & 0.0015 & 0.0054 & 0.0038 & 0.0031 & 0.0054 \\ 0.0115 & 0.0019 & 0.0096 & 0.0115 & 0.0077 & 0.0134 \\ 0.0054 & 0.0036 & 0.0054 & 0.0063 & 0.0045 & 0.0081 \end{bmatrix}$$

$$Vessel = \begin{bmatrix} 5 & 1 & 7 & 5 & 4 & 7 \\ 5 & 1 & 7 & 5 & 4 & 7 \\ 5 & 1 & 7 & 5 & 4 & 7 \\ 9 & 5 & 8 & 7 & 6 & 8 \end{bmatrix},$$

$$Normalised\ results = \begin{bmatrix} 0.0004 & 0.0001 & 0.0005 & 0.0004 & 0.0003 & 0.0005 \\ 0.0019 & 0.0004 & 0.0027 & 0.0019 & 0.0015 & 0.0027 \\ 0.0011 & 0.0002 & 0.0016 & 0.0011 & 0.0009 & 0.0016 \\ 0.0042 & 0.0023 & 0.0037 & 0.0033 & 0.0028 & 0.0037 \end{bmatrix}$$

$$Lazy\ Decky = \begin{bmatrix} 4 & 3 & 7 & 6 & 6 & 7 \\ 5 & 2 & 8 & 6 & 6 & 8 \\ 6 & 4 & 8 & 7 & 7 & 8 \end{bmatrix}$$

$$Normalised\ results = \begin{bmatrix} 0.0009 & 0.0007 & 0.0015 & 0.0013 & 0.0013 & 0.0015 \\ 0.0092 & 0.0037 & 0.0148 & 0.0111 & 0.0111 & 0.0148 \\ 0.0032 & 0.0022 & 0.0043 & 0.0038 & 0.0038 & 0.0043 \end{bmatrix}$$

$$Net = \begin{bmatrix} 2 & 2 & 8 & 6 & 5 & 8 \\ 3 & 3 & 7 & 6 & 5 & 8 \end{bmatrix}$$

$$Normalised\ results = \begin{bmatrix} 0.0017 & 0.0017 & 0.0067 & 0.0050 & 0.0042 & 0.0067 \\ 0.0005 & 0.0005 & 0.0011 & 0.0010 & 0.0008 & 0.0013 \end{bmatrix}$$

$$Gilson = \begin{bmatrix} 5 & 3 & 6 & 5 & 6 & 7 \\ 7 & 3 & 7 & 6 & 6 & 8 \end{bmatrix}$$

$$Normalised\ results = \begin{bmatrix} 0.0009 & 0.0005 & 0.0010 & 0.0009 & 0.0010 & 0.0012 \\ 0.0095 & 0.0041 & 0.0095 & 0.0082 & 0.0082 & 0.0109 \end{bmatrix}$$

8.6.9 Summary of results

The results obtained from sections 8.6.7 and 8.6.8 are collated to determine the best RCO. Tables 8.7 and 8.8 show the summary of these results obtained in percentage. Each of these tables represents 50% of the weight (as the RCO evaluation has been normalised) of the elements in Level Two of the hierarchy. The final ranking of the RCOs is achieved by adding the final ratings of each these tables for the respective RCOs. Table 8.9 shows the final results obtained for this analysis. From this table, it can be determined that the best control option to reduce the probability of occurrence and the severity (of human error) during the initial shooting operation is RCO 6. The results entail that by installing various warning and indication devices onto/for the equipment used for the initial shooting operation on a fishing vessel, the level of human error can be reduced and safe operation can be achieved.

	Derrick	Vessel	Lazy Decky	Net	Gilson	Total rating
RCO 1	*4.73%*	*1.22%*	*1.40%*	*0.26%*	*0.92%*	***8.53%***
RCO 2	*3.63%*	*0.19%*	*0.84%*	*0.26%*	*0.42%*	***5.34%***
RCO 3	*6.70%*	*0.47%*	*2.17%*	*0.79%*	*1.28%*	***11.42%***
RCO 4	*4.73%*	*0.32%*	*0.75%*	*0.32%*	*0.81%*	***6.94%***
RCO 5	*1.25%*	*0.66%*	*1.79%*	*0.42%*	*0.84%*	***4.97%***
RCO 6	*6.93%*	*1.14%*	*2.37%*	*1.05%*	*1.31%*	***12.81%***

Table 8.7 Summary of results for probability element

	Derrick	Vessel	Lazy Decky	Net	Gilson	Total rating
RCO 1	*5.73%*	*0.76%*	*1.33%*	*0.22%*	*1.04%*	***9.08%***
RCO 2	*1.30%*	*0.30%*	*0.65%*	*0.22%*	*0.46%*	***2.93%***
RCO 3	*5.02%*	*0.85%*	*2.06%*	*0.78%*	*1.06%*	***9.77%***
RCO 4	*5.15%*	*0.67%*	*1.61%*	*0.60%*	*0.90%*	***8.93%***
RCO 5	*3.91%*	*0.55%*	*1.61%*	*0.50%*	*0.92%*	***7.50%***
RCO 6	*6.87%*	*0.85%*	*2.06%*	*0.80%*	*1.21%*	***11.79%***

Table 8.8 Summary of results for severity element

	Derrick	Vessel	Lazy Decky	Net	Gilson	Total rating
RCO 1	*10.46%*	*1.98%*	*2.74%*	*0.48%*	*1.96%*	***17.61%***
RCO 2	*4.93%*	*0.49%*	*1.49%*	*0.48%*	*0.88%*	***8.27%***
RCO 3	*11.72%*	*1.33%*	*4.23%*	*1.57%*	*2.34%*	***21.19%***
RCO 4	*9.88%*	*0.99%*	*2.36%*	*0.91%*	*1.72%*	***15.87%***
RCO 5	*5.16%*	*1.21%*	*3.40%*	*0.92%*	*1.76%*	***12.46%***
RCO 6	*13.80%*	*1.99%*	*4.43%*	*1.85%*	*2.53%*	***24.60%***

Table 8.9 Final ranking of RCO

8.7 Conclusion

Human errors on fishing vessels have contributed to a great number of accidents in the past, as seen in chapter 2 (section 2.4). Almost 20% of all accidents on these vessels are caused by negligence/carelessness of the crew. As such, the ultimate aim for carrying out a human error assessment on fishing vessel is to determine the best method by which accidents caused by these errors can be reduced. This would entail decreasing the risk level by either reducing the probability of a human error occurring or the severity of the consequences.

This chapter proposes a method using AHP to achieve this aim. The approach integrates the risk control option within the human error assessment framework to determine the best option for the identified hazards. The advantages of using the proposed approach for fishing vessels include:

- The use of a flexible modeling and measurement approach to evaluation.
- The application of structure to facilitate decision making through the use of a model which imposes strict independence, ordinality, or homogeneity of preferences.
- Allowing the decision-maker to arrive at consistent and objective evaluations.
- The simplicity of the use of the model.
- The confidence that all human errors identified are evaluated (without being omitted by rationalisation) in the decision making process.
- The interaction between operator and machine is captured within the analysis.

In this chapter, only human errors are considered in the analysis. However, this can be extended to include failures induced by other causes, such as machinery failure. Hence, it can be easily integrated into the Formal Safety Assessment (FSA) framework as discussed in chapter 4. Step 4 of the FSA framework requires the evaluation of different risk control options. The AHP method presented here can be used for this purpose, and the results obtained from the analysis can be applied to step 5 of an FSA.

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AHP technique are discussed and the integration of such a technique within the FSA framework is described.

Finally conclusions and recommendations are provided in *Chapter 9*.

1.6 Contributions and Dissemination

The novel safety analysis techniques developed in this thesis will facilitate ship safety assessment in various situations. Although the methods developed were applied to fishing vessels, the results of the project can be tailored for safety analysis of any maritime and offshore engineering product with domain-specific knowledge. As these methods are subjective in nature, it proves useful for many engineering applications that lack reliable data.

Investigation results and findings are made available by publications in journals, presentation at international conferences and workshops. The deliverables arising from the research project are listed in Appendix 1.

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CHAPTER 9

CONCLUSIONS AND FURTHER WORK

Summary

This chapter concludes the thesis by summarising the results and presenting the findings of the research project carried out by the author, outlining the contributions to the safety analysis methodologies developed for fishing vessels. Salient points are emphasised and the areas where further effort and research is required to refine the developed methodologies are discussed.

9.1 Conclusions

The chapters in this thesis have thoroughly described the series of work carried out in this research project. The research started with the review of the development of safety and reliability assessment techniques in the maritime industry. It was found that the early application of these methods concerned military vessels, particularly the vessels' defence and offence systems. Gradually, the application of such techniques has found its way to merchant vessels. In the UK, the application of safety and reliability assessment techniques in the maritime industry has been principally related to the transportation of hazardous cargo. However, there has been some application in UK shipyards of Availability, Reliability and Maintainability (ARM) studies at the design stage.

Accident investigations over the years have provided valuable information for safety assessment of vessels. Lessons learnt from previous accidents have been used as a guide to produce rules and regulations to prevent similar accidents from happening. The capsize of the Herald of Free Enterprise in 1987 eventually resulted in the adoption of the International Safety Management (ISM) code. The Exxon Valdez accident in 1989 resulted in the international convention on Oil Pollution Preparedness, Response and Co-operation (OPRC) being established in 1990. Double hull or mid-deck structural requirements for new and existing oil tankers were subsequently applied [Sekimizu K., 1997]. The Scandinavian Star disaster in 1990 and the capsize of the Estonia in 1994 highlighted the role of human error in marine casualties and resulted in the introduction of the new Standards for Training, Certificates and Watchkeeping (STCW'95) for seafarers [Wang J. et. al., 1999; Wang J. and Zhang S., 2000]. The various databases available concerning these accidents and many more within the maritime industry are discussed in chapter 1. Most of the databases described, lack vital information for a comprehensive and accurate safety and reliability study. The missing information in these databases includes the relationship between the cause and effect of an accident and the chain of events that led to the accident. Specific component/equipment failure data is also lacking. However, the data that is available requires certain amount of formatting if it is to be used for a safety and reliability study.

The current rules and regulations governing fishing vessels are studied in chapter 2. The rules for fishing vessels were found to only address the vessel from the deck and accommodation line downwards. There has been no mention about the fishing gear and equipment associated with the fishing operation. However, there are several guidance documents that address the design, construction and equipment of fishing vessels [IMO, 1975a; IMO, 1975b; IMO, 1980; IMO, 1988]. These documents provide guidelines on various aspects of fishing vessels and are not compulsory.

Accident data gathered from the Marine Accident Investigation Branch (MAIB) concerning fishing vessels are analysed from 1992 to 1999. It was found that during this period, the percentage of vessels lost have been between 0.25% and 0.45% of the total registered vessels. Machinery damage was found to be the most common cause of accidents on fishing vessels, contributing 64% of all accidents. This is followed by foundering and flooding, grounding, collisions and contacts and finally fires and explosions. Each of these accident categories is analysed in more detail to provide a list of possible causes. Although it has been accepted that there is a certain amount of under reporting, the number of fishermen and fishing vessels lost are alarmingly high [MCA, 2000]. It can be deduced from this data analysis, that there is an urgent need to address the safety issues plaguing the fishing vessel industry.

In order to analyse the safety issues on fishing vessels, typical safety analysis techniques can be employed. These techniques include Preliminary Hazard Analysis (PHA), What-If Analysis, HAZard and OPerability analysis (HAZOP), Fault Tree Analysis (FTA), Event Tree Analysis (ETA) and many more as described in chapter 3. The review of these typical analysis methods is carried out, highlighting the advantages and limitations of each method. Safety analysis methods can be broadly divided into two major categories, namely, quantitative and qualitative analysis. The use of quantitative methods is often not suitable for fishing vessels, as the data available for such an analysis is limited. As such, the qualitative methods are preferred. Due to the subjective nature of qualitative methods, the use of such methods in safety studies has been critically debated [Wilson N., 1994; Klir G.J., 1994; Hardman D.K. and Ayton P., 1997]. Most of the subjective analysis methods express the probability of a failure occurring and its associated severity linguistically. These linguistic expressions are normally reflected along an ordinal scale (sometimes determined by a utility function) and are used by the analyst as a guide. The use of the HAZOP method is proposed for the identification of hazards on fishing vessels. The proposed method is based on the conventional HAZOP method developed for the chemical industry [Bendixen L.M. et. al., 1984]. The method seeks to identify hazards on fishing vessels based on the possible causes of the deviation for various process parameters under normal working conditions.

A more structured and systematic approach to assessing fishing vessel safety is described in chapter 4. Formal Safety Assessment (FSA) is a new approach to marine safety which involves using the techniques of risk and cost-benefit assessment to assist in the decision making process. FSA comprises of five steps, which include: hazard identification, the assessments of risk associated with those hazards, identifying the ways of managing the risks identified, carrying out a Cost Benefit Assessment (CBA) of the options and finally making a decisions on which options to select. The development of this technique was intended for the rule making process of the shipping industry. However, over the years it has been used on several occasions to improve operations and minimise costs of operating ships. The development of the method is traced back from the point of inception to the present day. Each step within the FSA framework is described and discussed in detail. A trial application of this method is conducted for a generic-fishing vessel. The experience gained from this trial application suggests that certain areas within this framework need improvement. This is mainly due to the lack of available data to carry out the analysis for a fishing vessel using the conventional approach of FSA [Marine Safety Agency, 1993]. In order to enhance the accuracy and the appropriateness of the FSA being applied to fishing vessels, novel methods have to be developed addressing the shortcomings of the five steps in the original FSA framework. These novel methods are presented in chapters 5, 6, 7 and 8. The proposed HAZOP method in chapter 2 can be integrated into step 1 of the FSA framework and the outcome of the analysis can be used in step 2 of the FSA.

A novel method capable of performing risk quantification and risk ranking is presented in chapter 5. This method utilises Fuzzy Set Theory (FST) and Fault Tree Analysis (FTA) to determine the probability of a failure occurring and the severity of the consequences. The use of FST is thought to be appropriate as it can handle the various forms of uncertainties that can manifest in the available data and the analysis itself. The probability of occurrence and the severity are expressed linguistically and the evaluation of risk is conducted with the use of a linguistic risk matrix. The outcome of this analysis is a risk ranking expressed in the form of a crisp number. The novel method developed reaps the advantages of presenting failure data in a structured manner using FTA and expressing uncertain data linguistically using FST. The application of this method was carried out on a Gilson winch operating system of a fishing vessel. The data obtained from the proposed HAZOP for fishing vessels can be used as the top events in the FTA. These top events are assigned linguistic terms representing the probability of occurrence and severity. From this analysis, it was found that the most critical component is the hydraulic oil filter and the least critical component is the control air cylinder. Integrating this method into step 2 of an FSA framework would increase its applicability to fishing vessels.

One of the main benefits of employing FSA for fishing vessels is the confidence that all hazards within the vessel will be identified and addressed. A typical method used to identify and screen these hazards is Failure Mode and Effects Analysis (FMEA).

Typically, an FMEA is carried out to identify all hazards that are present encompassing the design, structure and operation concerning the system being studied. A Risk Priority Number (RPN) is then assigned to each hazard identified. This RPN is used to screen the hazards and eliminate those hazards with a low RPN (considered to be of negligible importance to the system). However, there are several setbacks of using the RPN method and these shortcomings are discussed in chapter 6 [Gilchrist W., 1993]. It has been proven that the RPN method may produce inaccurate results, which could lead to certain hazards being overlooked [Pillay A. et. al., 2001a]. A novel method using fuzzy rule base and grey theory is proposed. The fuzzy rule base method integrates expert knowledge in a formal manner and evaluates each hazard for it probability of occurrence, severity and detectability. A risk ranking is then generated by defuzzyfying the various linguistic terms assigned to the three categories of evaluation mentioned above. These defuzzfied results represent the priority for attention of each hazard.

The grey theory method essentially produces the same results. However, there is an added advantage in employing this method as the weight of each category considered (the probability of occurrence, severity or detectability) can be incorporated. This entails that the analyst can determine in the analysis, which of these three categories are of more importance and rank each hazard accordingly. The three methods, that is, the traditional RPN, fuzzy rule base and grey theory methods are compared along side each other. The outcome from this comparison showed that the proposed novel approaches do not have the same disadvantages as the traditional RPN method. It is recommended that the fuzzy rule base approach be used for the hazard screening process in step 1 of the FSA framework and the grey theory method can be incorporated in step 2.

Step 3 of the FSA framework requires the analyst to determine the different ways by which the risk levels in a system can be reduced. Considering the safety issues on fishing vessels and the data presented in chapter 2, it is recommended that the maintenance strategies for these vessels be improved. The current maintenance on fishing vessels is reviewed in chapter 7 and the findings reflect that there are hardly any maintenance activities on the vessel apart from very basic routine maintenance. This would explain the high number of accidents caused by machinery failure [MAIB, 1999].

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Carrying out inspections on operating machinery would be a good starting point in developing a maintenance regime for fishing vessels. As such, a method to determine the optimal inspection period for equipment is proposed in chapter 7. In order to determine this optimal inspection period, three criteria are modelled using the delay time concept [Pillay A. et. al., 2001b]. These criteria include the down time suffered, cost incurred and the safety criticality of the system under study. The delay time represents the opportunity window within which an inspection and consequent repair (if an abnormality is identified) will deter a catastrophic failure from occurring [Christer A.H. et. al., 1995]. The application of the delay time concept requires information regarding the probability distribution function of the delay time. The application of this concept to fishing vessels will require subjective methods of estimating the probability distribution function of the delay time as the available data for this parameter is almost non-existent [Wang W., 1997]. However, to demonstrate the application of the delay time concept to fishing vessels, different known distributions were experimented with. The findings from these analyses reflected that the truncated standard normal and weibull distributions provided readable results [Pillay A. et. al., 2001c]. As such the truncated standard normal distribution was used throughout the analysis to determine the optimal inspection period for the different criteria modelled. The findings from the complete analysis suggest that an inspection of the fishing gear after every two fishing operation will contribute to the lowest cost and down time with an acceptable safety criticality level. The implementation of an inspection regime is just the first but very vital step in developing a maintenance strategy for fishing vessels. Data that is gathered from these routine inspections will provide a basis and critical information to develop a sound maintenance regime.

Implementing an inspection regime is only one of the many ways that the risk level in fishing vessels can be reduced. There are several other options such as redesigning the system, incorporating interlocks and alarm warnings and many more. Step 5 of the FSA deals with making decisions as to which Risk Control Option (RCO) would be best to implement. A method using Analytical Hierarchy Processing (AHP) is proposed in chapter 8 to select the most favourable RCO. The proposed method also integrates the assessment of human error in the AHP analysis. Human error has been determined to contribute to almost 80% of all maritime accidents. From the fishing vessel accident data collected, 20% of accidents have been identified as being caused by crew negligence [Loughran C.G., 1998]. As such, it is recommended that each RCO be evaluated for its effectiveness to reduce either the probability of human error occurring or the severity of the consequences. Unlike the traditional methods that are described in chapter 8, the AHP method does not omit any event that is identified by rationalisation. The proposed method also captures the interaction between operator and machine by identifying all the errors that could be committed by the operator while operating the machinery. The findings of this analysis suggest that the most effective RCO would be to install warning devices such as audio and visual alarms and indication either on the equipment or in the control rooms. Apart from analysing the human errors present in the system (as the cause of an accident), the analysis can be extended to include machinery failure due to material defects, environmental conditions, lack of procedures in place and many more. The AHP method allows for flexible modelling and re-structuring of the hierarchy. Apart from considering the effectiveness of the RCO, the proposed AHP method can be extended to incorporate several other criteria such as cost and feasibility of implementation. The proposed method can be integrated into step 5 of the FSA framework to complete the safety assessment process of a fishing vessel.

The initial aim of the project, which is to develop novel techniques that could be used for the safety assessment of fishing vessels, has been achieved. The novel methods developed and presented in this thesis can be integrated into various sections of the FSA framework. This ensures a structured approach to identifying hazards, quantifying the risks and evaluating and deciding the best risk control options. The proposed methods have been demonstrated to be technically viable, and further work is needed to demonstrate economic viability.

It is believed that the methodologies developed in this thesis possess enormous potential as valuable aids and effective alternatives in the area of formal safety assessment of fishing vessels. It is also believed that practical applications of these methodologies will result from utilisation by organisations that deal with safety problems with high uncertainty and insufficient data. In such cases, the implementation of the developed methodologies could have a high beneficial effect.

9.2 Further Work

There are several areas that may be worthwhile exploring and exploited on the basis of the methodologies developed in this thesis. These can be summarised by the points presented below:

- The concept of FSA should be widely used to arrive at suitable safety strategies for fishing vessels and such an analysis should be extended to address management issues. Due to the lack of a formal organisational structure of fishing vessels, there is a need to look at management issues and assess the impact on ship safety. The analysis should include ship and shore management and determine ways of improving the management structure to ensure safe and reliable operation of the fishing vessel.
- Formal training and education programmes should be developed for fishermen. This programme should not only highlight safety matters, but also extend to cover competency issues of the fishermen. Such a programme will be a starting point to cultivate a safety culture within the fishing industry. The outcome of an FSA analysis can be used to identify areas where such training and education are lacking and the programme can be developed addressing these areas.
- Designers of fishing vessels should adopt a "design for safety" approach as an integral part in the initial design stage. The "design for safety" methodology has been developed for marine offshore structure and may not be suitable for fishing vessels [Wang J. and Ruxton T., 1993]. Hence, research into this area may provide useful information for fishing vessel designers.
- Rules and regulation governing fishing vessels in the past seem to only consider the structure and stability of the vessels. These rules have to be extended to cover equipment, operating procedure, crew training and competency, inspection requirements by coast guard agencies, etc. It has been noted that the authorities have

addressed some of these aspects. However, there is a need to justify and rationalise each rule in order to account for the various costs that would be incurred by the vessel owners/operators as well as any stakeholder of the vessel. This can be achieved by using the FSA method. As such, development of rules applied to fishing vessel using the FSA method needs to be researched and explored.

- Quantitative risk assessment of fishing vessels is frequently inhibited by the lack of representative failure and repair statistics. Hence, there is a need to develop a database specifically for this type of vessels. Most databases available are only limited to failure data without identifying the chain of events or causes of failure. These are useful information that is required for a risk assessment. The reporting and recording format of accidents should be consistent and the data presented in the database should be formatted in such a way that it can be directly applied to the safety analysis techniques available. The current method of manipulating data has been noted to cause inaccurate analysis and this translates to a waste of time and resources [Vosburg J. and Kumar A., 2001].
- Maintenance activities have been identified in this thesis as one of the areas on fishing vessels that requires improvement. As such, further research into the development of a reliability and safety centred maintenance regime is required. The method proposed in chapter 7 only identifies the optimal inspection period of equipment on fishing vessels. This information has to be integrated with other maintenance concepts to develop a comprehensive regime that addresses all safety and reliability issue. The delay time concept could possibly be integrated with age-based replacement techniques [Sherwin D.J., 1999], availability-based maintenance [Organ M. et. al, 1997] and situational maintenance models [Riis J.O. et. al., 1997].
- The analysis of human errors on fishing vessels in chapter 8 concluded that the best way to reduce these errors is by introducing safety warning devices such as sensors and alarm for the timely detection of the condition. However, this may not be true over a long period of time when complacency sets in (especially with the activation of false alarms and the related problems associated with control systems). Hence, there is a need to further study areas of human performance prediction and reliability allocation to human performance. These aspects along with the psychological factors affecting fishing vessel crew should be studied in relation to

the man-machine interface and be integrated in the FSA framework to provide a comprehensive study of human error contribution to accidents.

Fishing vessels are slowly gaining "popularity" in the eyes of the governing bodies and private organisations, such as the Coast Guard Agencies, classification societies, marine insurers, charters and the International Maritime Organisation. Consequently, there is a need to develop safety assessment techniques for this industry. The work presented in this thesis can provide a basis for further study into fishing vessel safety.

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APPENDIX 1

Publication Arising from Work

Refereed Journal Papers

1. ***Pillay A.,*** Wang J., Wall, A., Ruxton T. (2001), "A maintenance study of fishing vessel equipment using delay time analysis", Journal of Quality in Maintenance Engineering, Vol.7, No.2, ISSN:1355-2511.

2. ***Pillay A.,*** Wang J., Wall A., Ruxton T. (2001), "Optimal inspection period for fishing vessel equipment: a cost and down time model using delay time analysis", Marine Technology, Volume 38, No.2, SNAME, ISSN: 0025-3316, pp. 122-129.

3. ***Pillay A.,*** Wang J., Wall, A., Ruxton T. (2000), "Risk assessment of fishing vessels using fuzzy set approach", Submitted 2000 to International Journal of Safety, Quality and Reliability.

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6. Kwon Y. S., Wang J., ***Pillay A.,*** Jung G. M. (2000), "Formal safety assessment and its application onto a fishing vessel – a preliminary study", IMarE in Korea, ISSN 1225 0767, pp. 1-4.

Refereed Conference Papers

1. ***Pillay A.***, Wang J., Jung G. M. and Kwon Y.S. (2001), "Optimal inspection period for fishing vessel equipment using delay time analysis model", Proceeding of the 4th Institute of Mathematics and its Applications (IMA) Conference, April 9-11, Salford University, United Kingdom.

2. ***Pillay A.***, Wang J., Jung G. M., Loughran C.G., I'Anson T., Wall A.D. and Ruxton T. (2001), "A modified Failure Mode and Effects Analysis (FMEA) using fuzzy approximate reasoning and grey relation analysis", 11th International Offshore and Polar Engineering Conference and Exhibition (ISOPE 2001), June 17-22, Stavanger, Norway.

3. ***Pillay A.*** and Wang J. (2001), "Human error assessment and decision making for fishing vessels using analytical hierarchy processing", Proceeding of the International Mechanical Engineering Congress and Exposition November 11-16, New York.

4. ***Pillay A.,*** Wang J., Wall, A., Ruxton T. (2000), "Analysis of fishing vessel failure data using fuzzy set approach", ESREL 2000 and SRA-Europe Annual Conference, Edinburgh, Scotland, UK, 14-17 May, Proceeding, Vol.2, ISBN: 90 5809 140 6, pp. 1005-1013.

5. Loughran C., ***Pillay A.,*** Wang J., Ruxton T. (1999), "Formal safety assessment of a generic fishing vessel", International Conference on Fishing Vessel Safety, April 12-16, Plymouth, United Kingdom.

6. Wang J., ***Pillay A.***, Wall A., Loughran C. (1999), "The latest development in marine safety assessment", Proceeding of the 4th International Conference On Reliability, Maintainability and Safety, May 18-21, 1999, Shanghai, China, pp. 711-719.

ABSTRACT

The work described in this thesis is concerned with the application of Formal Safety Assessment (FSA) to fishing vessels. Fishing vessels are generally smaller than most merchant vessels and the amount of data available to carry out a comprehensive safety assessment for this type of vessels is lacking. The traditional method of conducting an FSA employs typical safety analysis methods that require a certain amount of data. The failure and accident data available for fishing vessels are associated with a high degree of uncertainty and are considered unreliable. As such the work carried out in this thesis is directed to look at the development of novel safety analysis methods to address this problem.

This thesis proposes various subjective safety analysis methods for fishing vessels within the framework of the FSA technique. These steps comprise of hazard identification, the assessments of risk associated with those hazards, identifying the ways of managing the risks identified, carrying out a Cost Benefit Assessment (CBA) of the options and finally making a decisions on which options to select. Each step within the FSA framework is addressed by proposing a novel approach to accomplish the aim of the particular step.

In order to systematically and effectively identify and screen the hazards of fishing vessels, the HAZard and Operability (HAZOP) and Failure Mode and Effects Analysis (FMEA) approaches are proposed. The HAZOP approach identifies hazards by looking at the system operating parameters and determining how it can deviate from the normal operating conditions. The FMEA on the other hand looks at each component in the system to determine the ways that it can fail. The information gathered at this stage would include hazards that have a negligible risk implication. Hence, there is a need to carry out a hazard screening in order to reduce the number of hazards. The proposed FMEA method using fuzzy rule base and grey relation theory will identify and rank the risks associated with each hazard according to its priority for attention.

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9. Kwon Y. S., Wang J., ***Pillay A.***, Jung G. M. (2000), "Marine safety assessment", Proceeding of the Annual Reliability Conference in Korea, November, pp. 177-182.

10. Wang J., Yang J. B., Sii H. S., ***Pillay A.***, Kim S. (2000), "Marine and offshore risk assessment and control engineering", Proceeding of the Annual Conference of Chinese Automation and Computer Society in the UK (CACSUK), September 23-24, Loughborough, UK, ISBN: 0 9533890 2 2.

International workshop paper

1. ***Pillay A.*** and Wang J. (2000), "A cost and down time based inspection optimisation approach", European Safety and Reliability Association (ESRA) Workshop on Reliability and Risk Based Inspection Planning and ESRA Technical Committee on Offshore Safety, Swiss Federal Institute of Technology Institute for Structural Engineering, December 14-15, Zurich, Switzerland.

Invited Oral Presentations

1. ***Pillay A.***, Wang J and Loughran C.G. (2001), "Formal safety assessment of fishing vessel", Safety and Reliability Society Branch Meeting, EQE, 3rd April, Warrington, United Kingdom.

2. Loughran C.G, ***Pillay A.***, Wang J, Wall A., Ruxton T. (2000), "A generic fishing vessel safety assessment approach", Presented at the MCA meeting, December Session, Cardiff, Wales.

Poster Presentation

1. Wang J., ***Pillay A.*** and Saajedi A. (2000), "Marine and offshore technology research at Liverpool John Moores University", Presented in the UK Universities for North Sea Hydrocarbons Seminar and Workshop, November 30-December 1, Aberdeen Robert Gordon University, United Kingdom.

Book Review

1. Wang J., ***Pillay A.***, "Marine engineering challenges for the 21th century" Part 2, The Institute of Marine Engineers publications, Vol. 112, No.2, ISBN: 1 902536 40 1, IMarE Journal and Website.

APPENDIX 2

CODE OF PRACTICE FOR THE SAFETY OF SMALL FISHING VESSELS

CHECK LIST OF REQUIREMENTS

Decked Vessels
10m and above Registered Length to less than 12m Registered Length

Lifejackets - 1 per person
Liferafts
2 Lifebuoys (1 with 18m buoyant line attached) or
1 Lifebuoy (fitted with 18m buoyant line) +1 buoyant rescue quoit
3 Parachute flares
2 Hand-held flares
1 Smoke signal (buoyant or handheld)
1 Fire bucket + lanyard
1 Multi-purpose fire extinguisher (fire rating 5A/34B)
1 Fire blanket (light duty) in galley or cooking area (if applicable)
1 Fire pump + Hose or
1 Fire bucket + 1 Multi-purpose fire extinguisher (fire rating 5A/34B) + 1 fixed fire extinguishing system for the machinery space
1 Multi-purpose fire extinguisher for oil fires (fire rating 13A/113B)
VHF Radio - fixed or hand held
Bilge pump
Bilge alarm
Navigation lights and sound signals
Compass
Waterproof torch
Medical kit

Notes:
I. Equipment need not be MCA approved provided it is fit for its intended purpose.
II. "Decked vessels" means a vessel with a continuous watertight weather deck that extends from stem to stern and has positive freeboard throughout, in any condition of loading the vessel.
III. VHF using DSC is highly recommended in view of cessation of the Coastguard's Channel 16 dedicated headset watch on 1st February 2005.

CODE OF PRACTICE FOR THE SAFETY OF SMALL FISHING VESSELS

CHECK LIST OF REQUIREMENTS

All Decked Vessels
Up to 10m Registered Length

Lifejackets - 1 per person
2 Lifebuoys (1 with 18m buoyant line attached) or
1 Lifebuoy (fitted with 18m buoyancy line) +1 buoyant rescue quoit
3 Parachute flares
2 Hand-held flares
1 Smoke signal (buoyant or hand held)
1 Fire bucket + lanyard
1 Multi-purpose fire extinguisher (fire rating 5A/34B)
1 Fire blanket (light duty) in galley or cooking area (if applicable)
1 Fire pump + hose or 1 fire bucket
1 Multi-purpose fire extinguisher for oil fires (fire rating 13A/113B)
VHF radio – fixed or hand held
Bilge pump
Bilge alarm
Navigation lights and sound signals
Compass
Waterproof torch
Medical kit

Notes:

I. Equipment need not be MCA approved provided it is fit for its intended purpose.

II. "Decked vessels" means a vessel with a continuous watertight weather deck that extends from stem to stern and has positive freeboard throughout, in any condition of loading the vessel.

III. VHF using Digital Selective Calling (DSC) is highly recommended in view of cessation of the Coastguard's Channel 16 dedicated headset watch on 1st February 2005.

CODE OF PRACTICE FOR THE SAFETY OF SMALL FISHING VESSELS

CHECK LIST OF REQUIREMENTS

Open Vessels
7m and above to less than 12m Registered Length

Lifejackets - 1 per person
2 Lifebuoys (1 with 18m buoyant line attached) or 1 lifebuoy (with 18m buoyant line) +1 buoyant rescue quoit
3 Parachute flares
2 Hand-held flares
1 Smoke signal (buoyant or hand held)
1 Fire bucket + lanyard
1 Multi-purpose fire extinguisher (fire rating 5A/34B)
1 Fire blanket (light duty) in galley or cooking area (if applicable)
1 Fire pump + hose or 1 fire bucket
1 Multi-purpose fire extinguisher for oil fires (fire rating 13A/113B)
VHF Radio – fixed or hand held
Bilge pump
Navigation lights and sound signals
Compass
Waterproof torch
Medical kit

Notes:

I. Equipment need not be MCA approved provided it is fit for its intended purpose.

II. VHF using Digital Selective Calling (DSC) is highly recommended in view of cessation of the Coastguard's Channel 16 dedicated headset watch on 1st February 2005.

CODE OF PRACTICE FOR THE SAFETY OF SMALL FISHING VESSELS

CHECK LIST OF REQUIREMENTS

OPEN Vessels
Less than 7m Registered Length

Lifejackets – 1 per person
1 Lifebuoy (with 18m buoyant line attached)
2 Parachute flares
2 Hand-held flares
1 Smoke signal (buoyant or hand held)
1 Fire bucket + lanyard
1 Multi-purpose fire extinguisher (fire rating 5A/34B) - if vessel has in- board engine
1 Fire blanket (light duty) if vessel has galley or cooking area
VHF Radio – fixed or hand held
Bailer
Navigation lights and sound signals
Compass
Waterproof torch
Medical kit

Notes:

I. Equipment need not be MCA approved provided it is fit for its intended purpose.

II. VHF using Digital Selective Calling (DSC) is highly recommended in view of cessation of the Coastguard's Channel 16 dedicated headset watch on 1st February 2005.

APPENDIX 3

Fishing Vessel (Safety Provisions) Safety Rules 1975

Arrangement of rules

PART I – GENERAL

Rule

1. Citation, application, commencement, interpretation and amendment.

PART II – FISHING VESSEL CONSTRUCTION RULES

A – HULL (INCLUDING SUPERSTRUCURES) AND EQUIPMENT

2. Structural strength

B – WATERTIGHT INTEGRITY

3. Closing arrangements.
4. Doors
5. Hatchway covers.
6. Machinery space openings.
7. Other deck openings.
8. Ventilators.
9. Air pipes.
10. Side scuttles and skylights.
11. Side openings.
12. Inlets, discharges and scuppers other than deck scuppers.
13. Heights oh hatchway coamings, doorway sills, ventilators and air pipes.
14. Freeing ports.

C – FREEBOARD AND STABILITY

15. Freeboard.
16. Stability.

D – BOILERS AND MACHINERY

17. General.
18. Boiler feed systems.
19. Steam pipe systems.
20. Machinery.
21. Means for going astern.
22. Shafts.
23. Exhaust systems.

24. Air pressure systems.
25. Cooling water systems – vessels of 24.4 meters in length and over.
26. Cooling water systems – vessels of 12 meters in lengths and over but less than 24.4 meters in length.
27. Oil systems for lubricating, cooling and control – vessels of 24.4 meters in length and over.
28. Oil systems for lubricating, cooling and control – vessels of 12 meters in length and over but less than 24.4 meters in length.
29. Oil fuel installations (boilers and machinery) – general.
30. Oil fuel installations (boilers and machinery) – vessels of 24.4 meters in length and over.
31. Oil fuel installations (boilers and machinery) – vessels of 12 meters in length and over but less than 24.4 meters in length.
32. Oil fuel installations (cooking ranges and heating appliances).
33. Ventilation.
34. Liquefied petroleum gas installations (cooking ranges and heating appliances).
35. Storage of flammable liquids, toxic liquids, toxic gases and compressed gases.

E – BILGE PUMPING ARRANGEMENTS

36. Requirements for vessels of 24.4 meters in length and over.
37. Requirements for vessels of 12 meters in length and over but less than 24.4 meters in length.

F – ELECTRICAL EQUIPMENT AND INSTALLATIONS

38. General.
39. Distribution systems.
40. Electrical precautions.
41. Requirements for vessels of 24.4 meters in length and over.
42. Requirements for vessels of 12 meters in length and over but less than 24.4 meters in length.
43. Accumulator (storage) batteries and associated charging equipment.

G – MISCELLANEOUS PLANT AND EQUIPMENT

44. Watertight doors.
45. Steering gear – vessels of 24.4 meters in length and over fitted with rudders.
46. Steering gear – vessels of 12 meters in length and over but less than 24.4 meters in length fitted with rudders.
47. Steering gear – vessels of 12 meters in length and over fitted with steering devices other than rudders.
48. Electrical and electro-hydraulic steering gear.
49. Communication between wheelhouse and engine room – vessels of 24.4 meters in length and over.
50. Controllable pitch propellers.
51. Refrigerating plants.
52. Anchors and chain cables.

53. Spare gear.
54. Winches, tackles and lifting gear.

H – STRUCTURAL FIRE PROTECTION AND FIRE DETECTION

55. Structural fire protection – general.
56. Structural fire protection – vessels with hulls constructed of steel or other equivalent material.
57. Structural fire protection – vessels with hulls constructed of glass reinforced plastic.
58. Structural fire protection – vessels with hulls constructed of wood.
59. Ventilation systems.
60. Means of escape.
61. Space heaters and cooking stoves.
62. Automatic fire detection systems

I – PROTECTION OF THE CREW

63. Bulwarks, guard rails and guard wires.
64. Openings in decks.
65. Stairways and ladders.

J – NAUTICAL EQUIPMENT

66. Compasses – requirements for vessels of 45 meters in length and over.
67. Compasses – requirements for vessels of 12 meters in length and over but less than 45 meters in length.
68. Compasses – general requirements.
69. Sounding equipment.
70. Nautical publications.
71. Flags and signalling equipment.
72. Pilot ladders.

K – DOCUMENTATION TO BE CARRIED ON VESSELS

73. Record of particulars to be kept on vessel.
74. Information as to stability to be kept on vessel.
75. Information on loading and ballasting to be kept on vessel.

PART III – RULES FOR LIFE-SAVING APPLIANCES

A - LIFE-SAVING APPLIANCES AND EQUIPMENT

76. Requirements for vessels of 75 meters in length and over.
77. Requirements for vessels of 45 meters in length and over but less than 75 meters in length.
78. Requirements for vessels of 24.4 meters in length and over but less than 45 meters in length.

79. Requirements for vessels of 17 meters in length and over but less than 24.4 meters in length.
80. Requirements for vessels of 12 meters in length and over but less than 17 meters in length.
81. Requirements for vessels less than 12 meters in length.
82. General requirements for lifeboats.
83. General requirements for Class C boats.
84. General requirements for inflatable boats.
85. General requirements for life rafts.
86. Marking of lifeboats, Class C boats, inflatable boats and life rafts.
87. Requirements for lifebuoys.
88. Requirements for self-igniting lights attached to lifebuoys.
89. Requirements for line-throwing appliances.
90. Equipment for lifeboats and Class C boats.
91. Equipment for inflatable boats.
92. Rations for lifeboats.
93. Security of equipment and rations in lifeboats, Class C boats and inflatable boats.
94. Equipment and rations for life rafts.
95. General provisions relating to the stowage and handling of life-saving appliances.
96. Stowage and handling of lifeboats and Class C boats.
97. Stowage and handling of inflatable boats.
98. Stowage and handling of life rafts, lifebuoys and lifejackets.
99. Embarkation into lifeboats, Class C boats, inflatable boats and life rafts.
100. Storage of pyrotechnic distress signals.

B – FIRE APPLIANCES

101. Requirements for vessels of 60 meters in length or over.
102. Requirements for vessels of 45 meters in length and over but less than 60 meters in length.
103. Requirements for vessels of 24.4 meters in length and over but less than 45 meters in length.
104. Requirements for vessels of 21 meters in length and over but less than 24.4 meters in length.
105. Requirements for vessels of 9 meters in length and over but less than 21 meters in length.
106. Requirements for vessels less than 9 meters in length.
107. Requirements for fire pumps.
108. Requirements for the fire main, water service pipes and hydrants.
109. Requirements for fire hoses, nozzles, etc.
110. Requirements for fire extinguishers.
111. Requirements for fire alarm and fire detection systems.
112. Requirements for fixed pressure water-spraying systems for machinery spaces.
113. Requirements for fixed fire smothering gas and steam installations.
114. Requirements for fixed foam fire extinguishing installations.
115. Requirements for fireman's outfits.
116. Means for stopping machinery, shutting off fuel oil suction pipes and closing openings.

CHAPTER 2

FISHING VESSEL SAFETY

Summary

This chapter reviews the current rules and regulations governing fishing vessels and presents the safety programmes implemented by the governing bodies. Accident data collected from the Marine Accident Investigation Branch are presented and an analysis is carried out to determine the most common cause of accidents on fishing vessels.

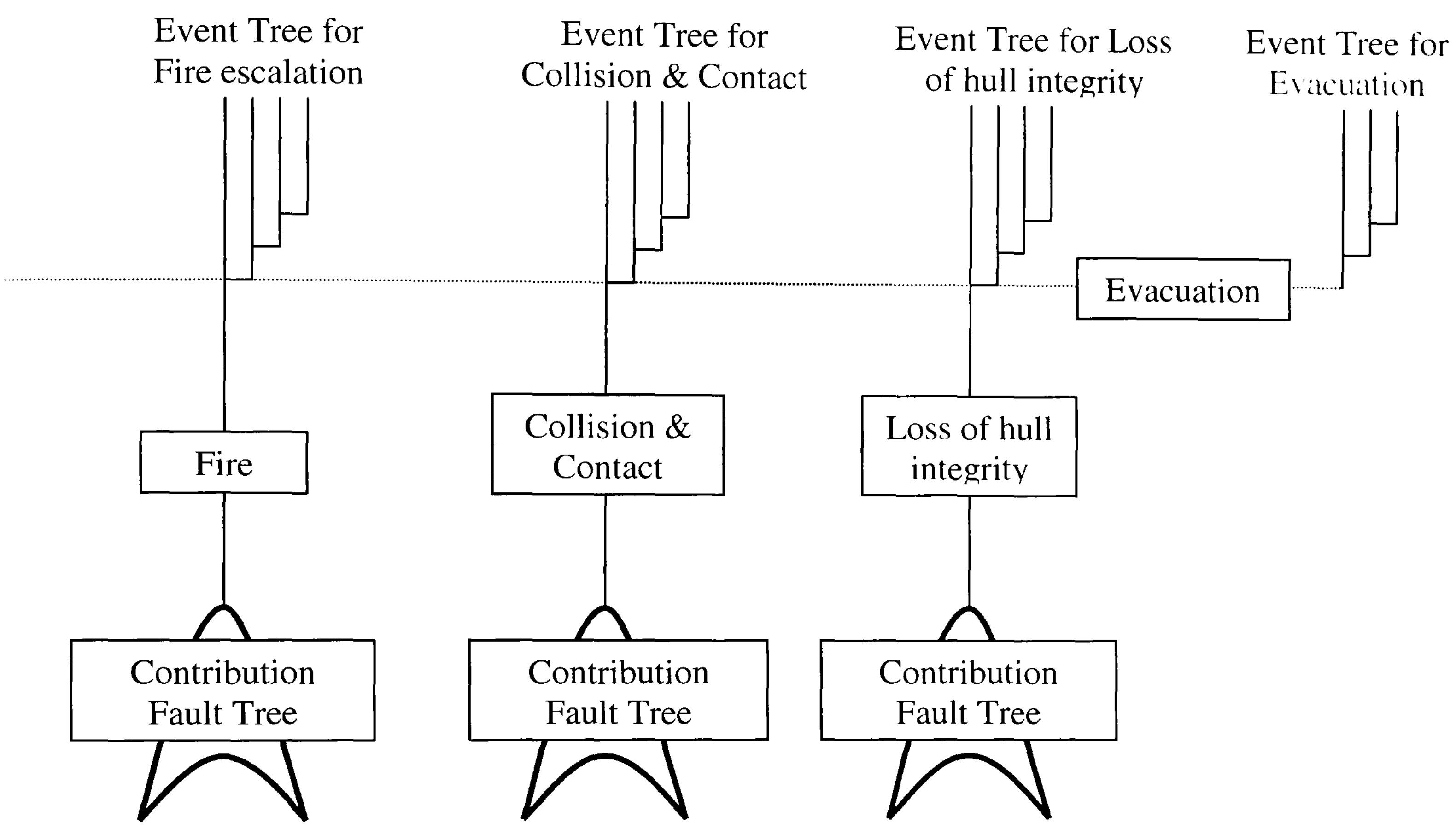
2.1 Introduction

Recognising the need for attention to safety of commercial fishing vessels, the IMO organised an international conference, which culminated in the Torremolinos International Convention for the safety of fishing vessels in 1977 [IMO, 1977]. It established uniform principles and rules regarding design, construction and equipment for fishing vessels 24m (79 feet) in length and over. This convention was a major milestone. It provided benchmarks for improving safety, and many fishing nations have adopted its measures into their marine safety programmes.

The IMO convention on Standard of Training, Certification and Watch keeping for seafarers (STCW) 1978 is another important factor. Although the STCW 1978 specifically exempts fishing vessels, it has inspired efforts to develop personnel qualification standards (STCW 95 also exempts fishing vessels). Notable among these efforts is the Document for Guidance on Fishermen's Training and Certification [IMO, 1988] and the Code of Safety for Fishermen and Fishing Vessels [IMO, 1975a]. Other IMO codes and guidelines include the voluntary guidelines for the design, construction and equipment of small fishing vessels [IMO, 1980] and the code of safety for fishermen and vessel design and construction [IMO, 1975b]. These standards are jointly prepared by IMO and two other United Nations subsidiaries, Food and Agricultural

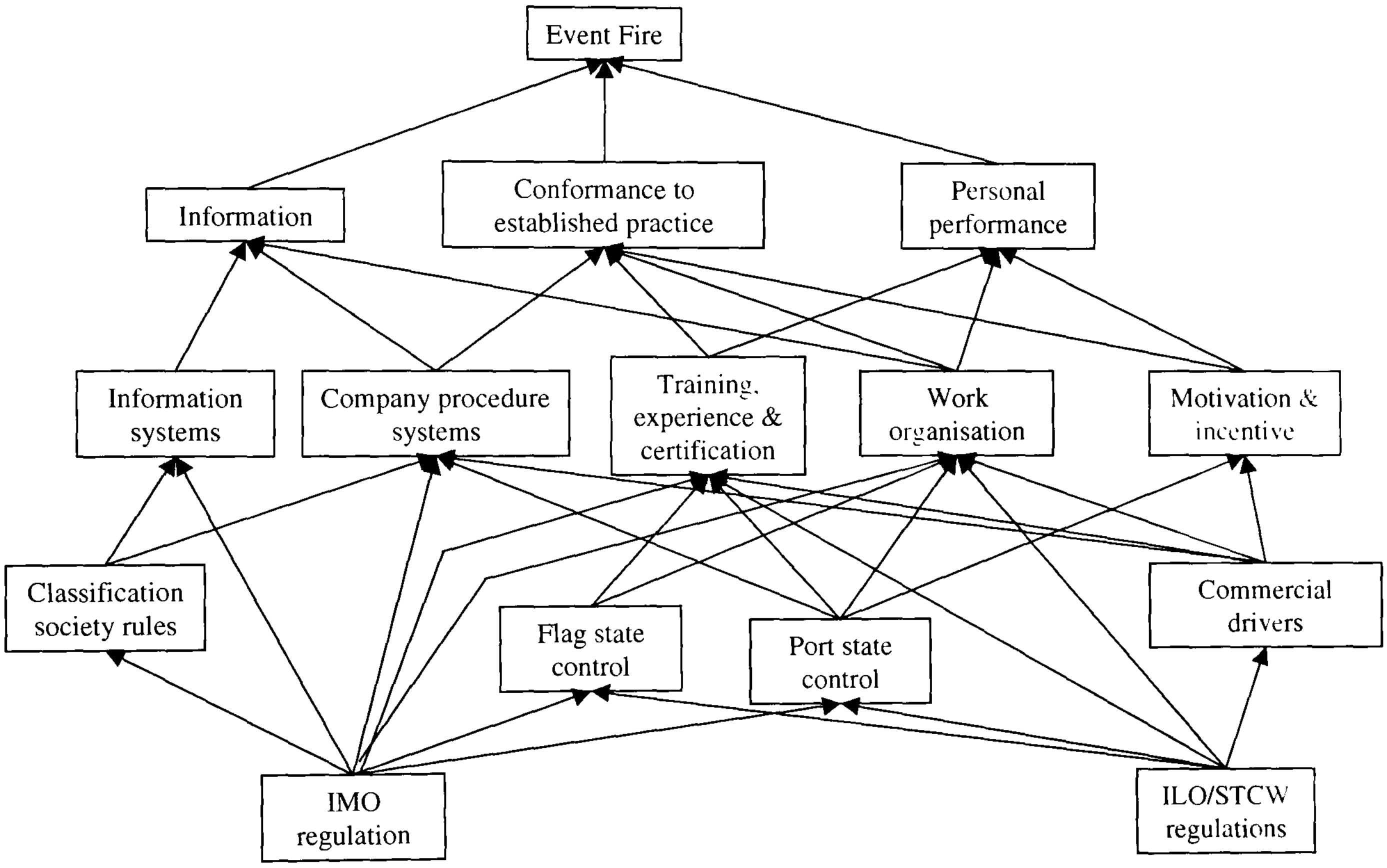
APPENDIX 4

Risk Contribution Tree (RCT)



APPENDIX 5

Influence Diagram



Organisation (FAO) and International Labour Organisation (ILO). They provide guidance on training and education and detailed curriculum development.

There are strong safety programmes among IMO member states that include equipment standards, inspection requirements and certification or licensing of vessel operators and crew. These programmes vary in each country for example; Canada, Norway and the UK have extensive requirements, while other countries are less stringent. Generally vessels about 15m or larger are addressed; however some countries address vessels as small as 9m, such as New Zealand and 12m as in the UK.

In the UK, comprehensive regulations have come into force since 1975. Surveys and certification of fishing vessels with the length of 12m or longer are required; they apply to about 2000 vessels. For vessels with the length of over 16.5m, deck officers and engineers have comprehensive entry level professional training, certification, manning and watch keeping requirements.

Studies on the effect of compulsory programmes have been conducted in Norway, The Netherlands, UK and Spain, but they have tended to focus on training, statistics and causes of accidents rather than performance of technical systems in relation to compulsory programmes. It appears that fatalities have generally been reduced, while the rates of incidence for injuries related to vessel casualties and workplace accidents appear unchanged. The lack of apparent change in injury rates may be related to working conditions and methods, vessel design, training deficiencies and changes in the number of fishing vessels and fishermen [Carbajosa J.M., 1989; Dahle E.A. and Weerasekara J.C.D., 1989; Hoefnagal W.A.M. and Bouwman K., 1989; Stoop J., 1989]. The number of vessel casualties over the years has changed. For example, in the UK, since safety rules were applied to all vessels over 12m during the mid 1980's, the number of losses of these vessels has significantly reduced. However, losses of vessels under 12m have more than doubled, perhaps partly because of a large increase in the number of vessels under 12m, to which only life saving and fire safety government regulations apply [Hopper A.G. and Dean A.J., 1992].

2.2 The Code of Practice for the Safety of Small Fishing Vessels

The development of a code of practice for small fishing vessels marked the beginning of the first major review of fishing vessel safety regulations since 1975. The principal aim in developing the code was to update the safety equipment requirements for small fishing vessels. Its secondary aim is to build on the concept of hazard identification and risk assessment that already applies to health and safety on board the vessel, and introduce an assessment by owners of the fitness of their vessels [House of Commons, 2000].

The Code of Practice for the safety of small fishing vessels has been effective since the 1st of April 2001. The aim of this Code of Practice is to improve safety in the under 12 meter sector of the fishing industry and to raise the safety awareness of all those involved with the construction, operation and maintenance of fishing vessels with a registered length of less than 12 meters.

2.2.1 Development

In 1992 the National Audit Office, in its report entitled "Department of Transport: Ship Safety" noted an increase in the fishing vessel accident rate from 1978 to 1989, due in part to an increase in the numbers of smaller vessels [National Audit Office, 1992]. It observed the absence, until 1990, of any programme of inspection of fishing vessels with a registered length of less than 12 meters. At about the same time, the House of Lords Select Committee on Science and Technology recommended that fishing vessels down to 7m in length should be brought within the licensing, crew certification and structural safety regimes.

In response, the Surveyor General's Organisation of the Department of Transport (now the Maritime & Coastguard Agency (MCA)), in consultation with industry members of the Fishing Industry Safety Group (FISG), decided to develop a Code of Practice for fishing vessels with a registered length of less than 12 meters. This Code has been developed by the MCA. The content of the Code has been the subject of extensive discussion with representatives of the under 12 meter sector of the fishing industry within a Steering Committee set up by FISG to oversee the Code's development. The Code applies from the 1st of April 2001 to all United Kingdom registered fishing vessels with a registered length of less than 12 meters.

2.2.2 Code requirements

To comply with the Code, a vessel owner will be required:

- To carry safety equipment on the vessel appropriate to its length and construction (i.e. decked or open). The equipment checklist is given in Appendix 2.
- To complete, or arrange completion of an assessment of the health and safety risks arising in the normal course of work activities or duties on the vessel in accordance with the provisions of the Merchant Shipping and Fishing Vessels (Health and Safety at Work) Regulations 1997 and MGN 20 (M+F).
- To certify annually that the vessel complies with the Code, by declaring that the safety equipment has been properly maintained and serviced in accordance with manufacturers' recommendations and that an appropriate, up-to-date health and safety risk assessment has been completed.
- To present the vessel for inspection either voluntarily or as requested by the MCA.

Appendix 2 gives the checklist of requirements for the Code of Practice for the safety of small fishing vessels in 4 categories. The vessels addressed in this code of practice include: 1) Decked vessels 10m and above registered length to less than 12m registered length, 2) All decked vessels up to 10m registered length 3) Open vessels 7m and above to less than 12m registered length and 4) Open vessels less than 7m registered length.

2.3 The Fishing Vessels (Safety Provisions) Safety Rules 1975

In 1968, three vessels were tragically lost off the coast of Iceland. The investigation of these three vessels determines the loss as 'capsizing due to ice accumulation'. Following the official inquiry into these losses, a rule regime was investigated which eventually arrived on the statute as "The Fishing Vessels (Safety Provisions) Safety

Rules 1975". Unfortunately the formulation of the rules did not result in an analysis of the organisational or human failing, present in many safety tragedies within the fishing community. The rules are primarily concerned with vessels of over 12 meters registered length. Smaller vessels are addressed, but only life saving appliances and firefighting measures are included. Appendix 3 gives a list of all equipment addressed in The Fishing Vessel (Safety Provisions) Safety Rules 1975. These rules do not concern themselves with the whole vessel, but may be noted to consider the vessel from the deck and accommodation line downwards. The winches, wires and fishing equipment are not covered by the rules.

Following the introduction of the 1975 Rule, the European Common Fisheries policy brought in a licensing scheme for vessels over 10 meters. This coupled with a de-commissioning scheme for larger vessels, resulted in a huge increase in the number of under 10 meter vessels. These vessels did not need licenses to fish and need not comply with the majority of the 1975 Rules. However, in 1996, the Ministry of Agriculture Fisheries and Food introduced fishing licenses for vessels of under 10 meters overall length. The introduction of this law has reduced the size of the fleet. The greatest incidence of risk has now moved to vessels in the 7 to 20 meter range, with particular safety concern for those vessels under 12 meters. Following concern emanating from the Parliament, inspections on these under 12 meter vessels have been requested. Since 1993, under 12 meter vessels have been subjected to safety inspection.

2.4 Accident Data

Comparisons of the safety record of the fishing industry with other industries indicate that the industry continues to be the most dangerous by a significant margin. In 1995/96 there were 77 fatal injuries per 100,000 fishermen as opposed to 23.2 per 100,000 employees in the mining and quarrying industry (the next highest category in that year) [MAIB, 1995]. In 1992 there were 494 reported fishing vessel accidents from a fleet of 10,953 vessels. In 1997, figures indicate 485 reported fishing vessel accidents from a significantly reduced fleet of 7,779 vessels. These statistics do not include personal accidents to fishermen while at sea; it is believed that these are under-reported [MAIB, 1997].

The accident data presented in this section are predominantly gathered from the Marine Accident Investigation Branch (MAIB). The MAIB is a totally independent unit within the Department of the Environment Transport and the Regions (DETR) and reports directly to the Secretary of State. The MAIB received 1,418 accident and incident reports in 1999. Accidents to ships accounted for 641 of those reports.

The data presented here is collected from 1992 to 1999 and reflects all the reported incidents and accidents relating to fishing vessels. It is thought that the actual accident and incident figures are much higher than what is presented here, as many accidents are not reported to the coastguard authorities.

The graph in figure 2.1 shows the total number of vessels lost (primary y-axis) and total number of vessels registered (secondary y-axis) from 1992 to 1999. These figures include all vessel sizes ranging from under 12 meter to over 24 meter. From this graph, it is evident that the percentage of vessels lost have increased from 1992 to 1994 and then reduced from 1994 to 1998. From 1998 onwards, it is noted that there has been a sharp increase in the percentage of vessels lost. Overall, the percentage of vessels lost have been between 0.27% (minimum in 1997/98) and 0.45% (maximum in 1999) of the total registered vessels, as seen in figure 2.2

There were approximately 7,460 UK-registered fishing vessels in 1999 (end December 1999 figure). During the year 370 accidents and incidents involving these vessels were reported to the MAIB. 33 fishing vessels were lost which at 0.45% of the total fleet represents the highest rate since 1994. Machinery damage is noted as the main contributor to the high number of accidents as seen in the pie chart of figure 2.3.

An analysis of the data from previous years shows that machinery damage has contributed to over 50% of all accidents. This could be attributed to several factors including poorly maintained equipment, incorrect operation, age, lack of automation etc.

The graph in figure 2.4 shows the number of accidents caused by machinery damage from 1994 to 1999. Although the figures indicate a decreasing trend, the number of accidents related to this category is still high and certainly unacceptable from a safety perspective.

The next highest contributor to accidents is found to be flooding and foundering followed by grounding and then collision and contact. A comparison of all accident types is made as seen in figure 2.5. Flooding and foundering is estimated to cause almost 15% to 20% of accidents on fishing vessels.

These data is cumulated and presented as a pie chart in figure 2.6 to reveal the contribution of each accident type for the sampling period. As revealed earlier, machinery damage is found to be the most common cause of accidents on fishing vessels, contributing 64.4% of all accidents. Foundering and flooding (14.2%), grounding (10.2%), collision and contacts (5.7%), and fires and explosions (2.9%) follow.

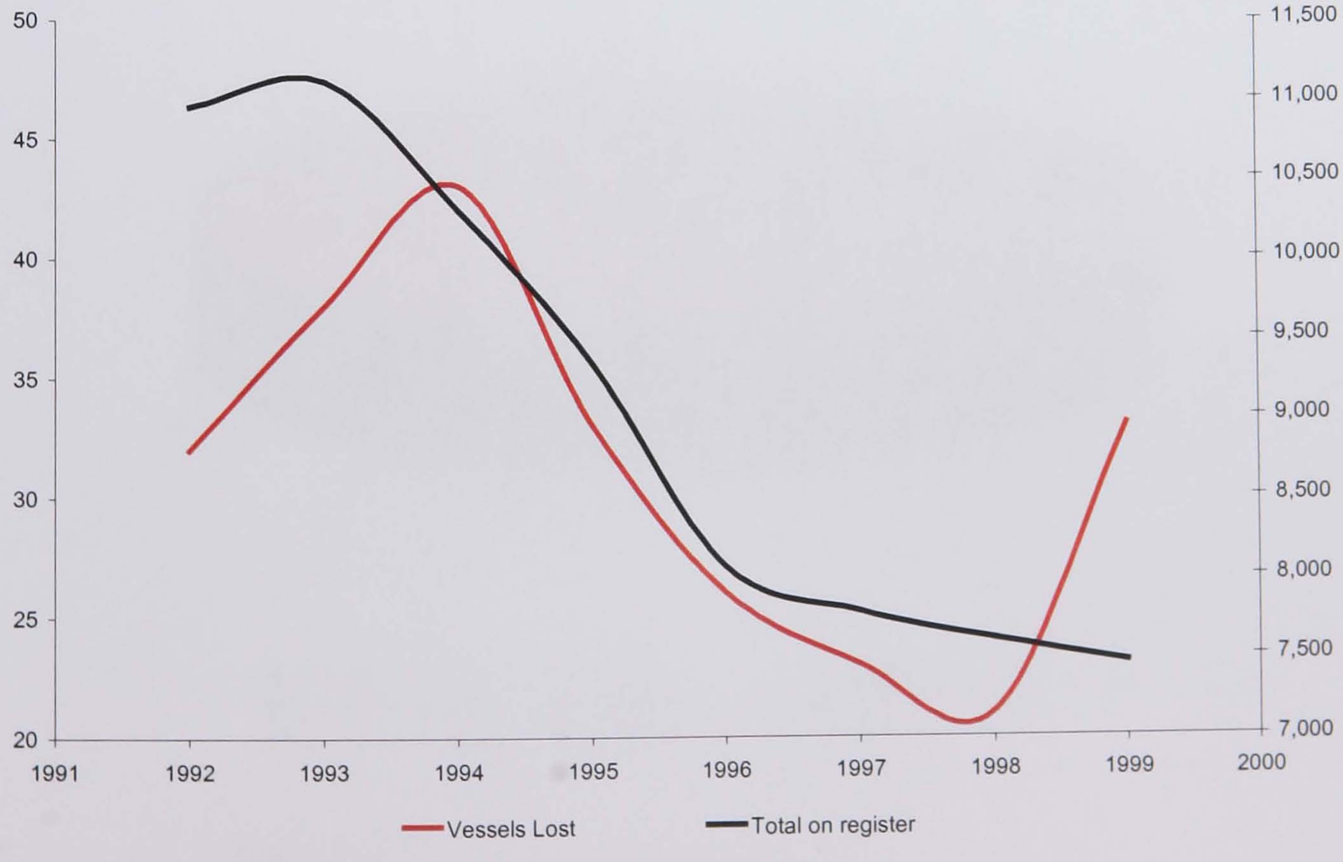


Figure 2.1 Vessels registered and lost (1992-1999)

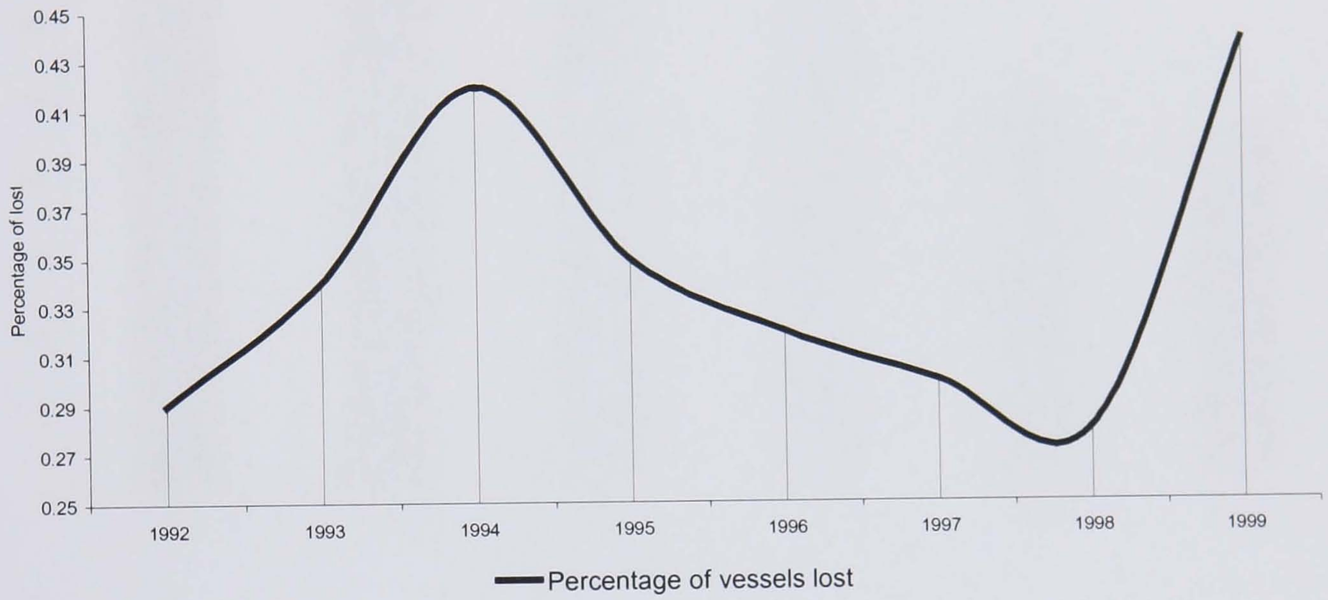


Figure 2.2 Proportion of vessels lost

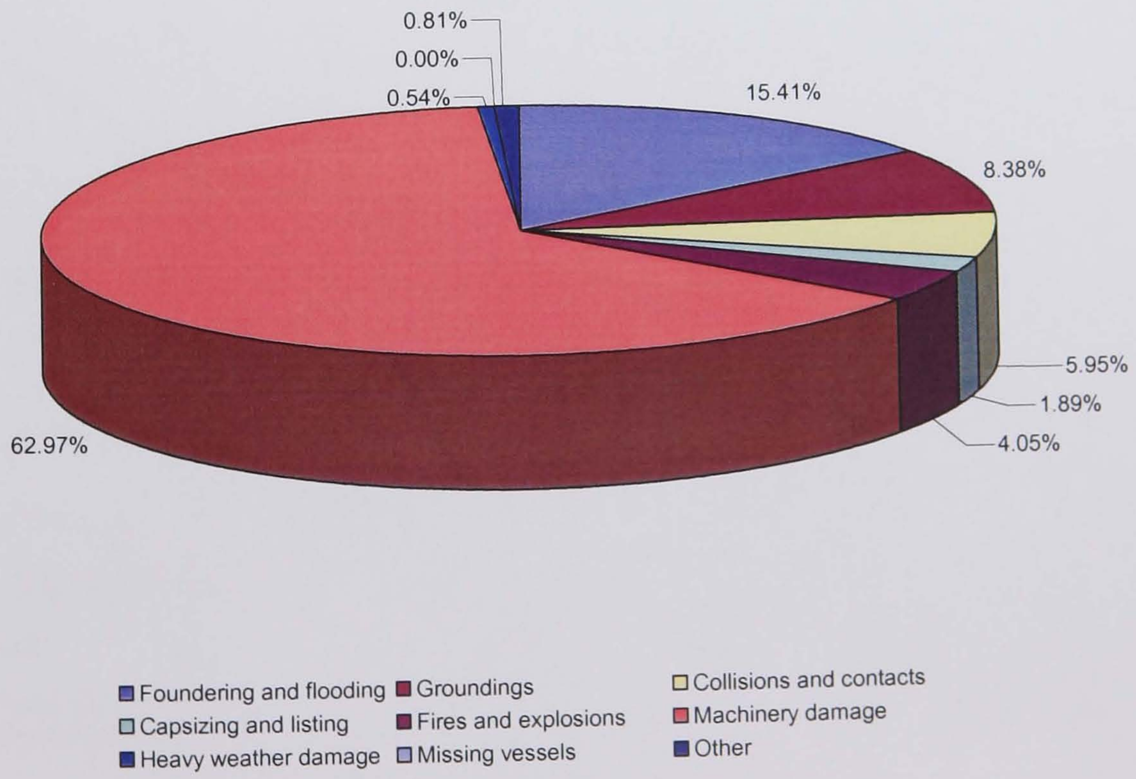


Figure 2.3 Accidents to vessels by accident type in 1999

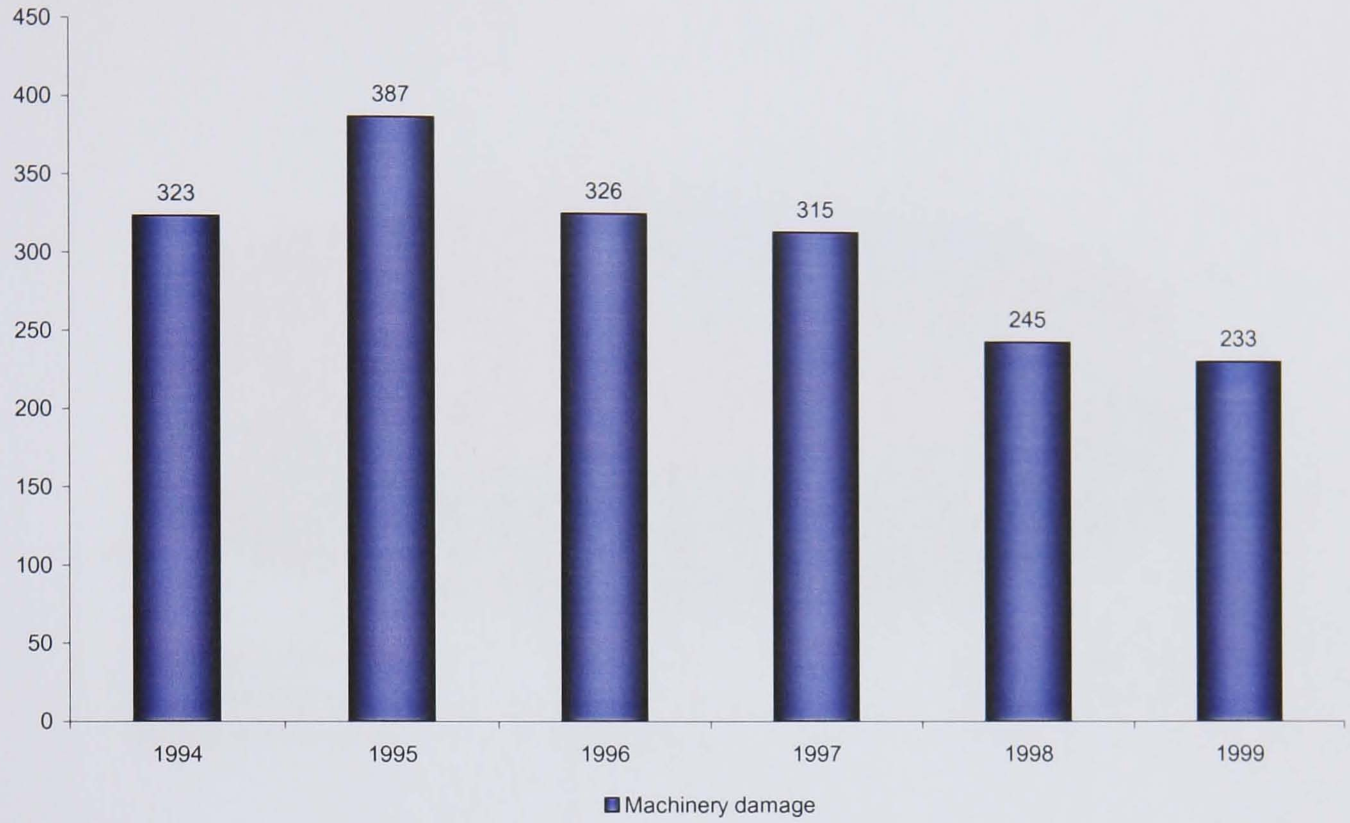


Figure 2.4 Accidents caused by machinery damage

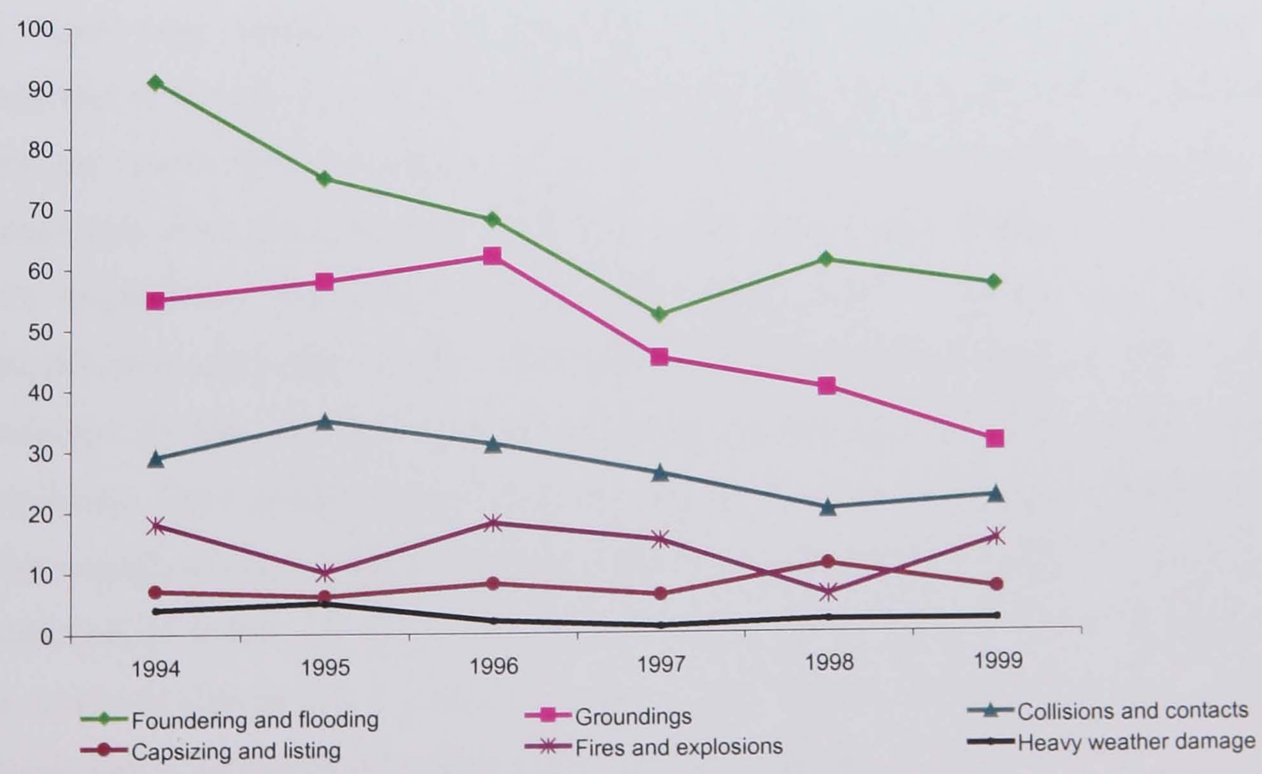


Figure 2.5 Accidents to fishing vessels by accident type

A method using Fuzzy Set Theory (FST) and Fault Tree Analysis (FTA) is proposed to evaluate the hazards identified by the proposed HAZOP and FMEA method. The integration of FST and FTA provides a practical means of assessing the chain of events from the basic (primary events) up to the top event (undesirable event) of the fault tree. This method utilises linguistic terms to express the probability of failures of the basic events and the severity of the consequences. As such, these parameters are expressed in a natural manner reflecting the uncertainty in the data used.

The initial analysis of a fishing vessel revealed that machinery failures due to lack of maintenance activities were the cause of many accidents. Hence, the development of a maintenance regime is identified to be one of the ways to manage the risks that were evaluated by the FTA. A method using the delay time concept is proposed to determine the optimal inspection period for fishing vessel equipment. Most fishing vessels do not have a maintenance regime in place, therefore it is proposed that an inspection regime be implemented to gather enough data to develop a comprehensive maintenance regime. The delay time concept provides an effective means of modelling the inspection period for fishing vessels as it is based on actual failures rather than generic failure data.

Human errors have been identified as one of the areas that need further research. A method to assess the human errors on fishing vessels using Analytical Hierarchy Processing (AHP) is proposed. This proposed approach integrates the decision making phase of different risk control option available to fishing vessels. The outcome of this analysis will assist in the decision making process of the FSA framework. Finally the results of the research project are summarised and the areas where further effort is required to improve the developed methodologies are outlined.

To demonstrate the methodologies developed in this thesis, the operating system of a hydraulic winch on a fishing vessel is used. The data was obtained from an industrial collaborator that owns and operates fishing vessels in the United Kingdom. A diagrammatic representation of the original contribution presented in this thesis is shown in figure 1.

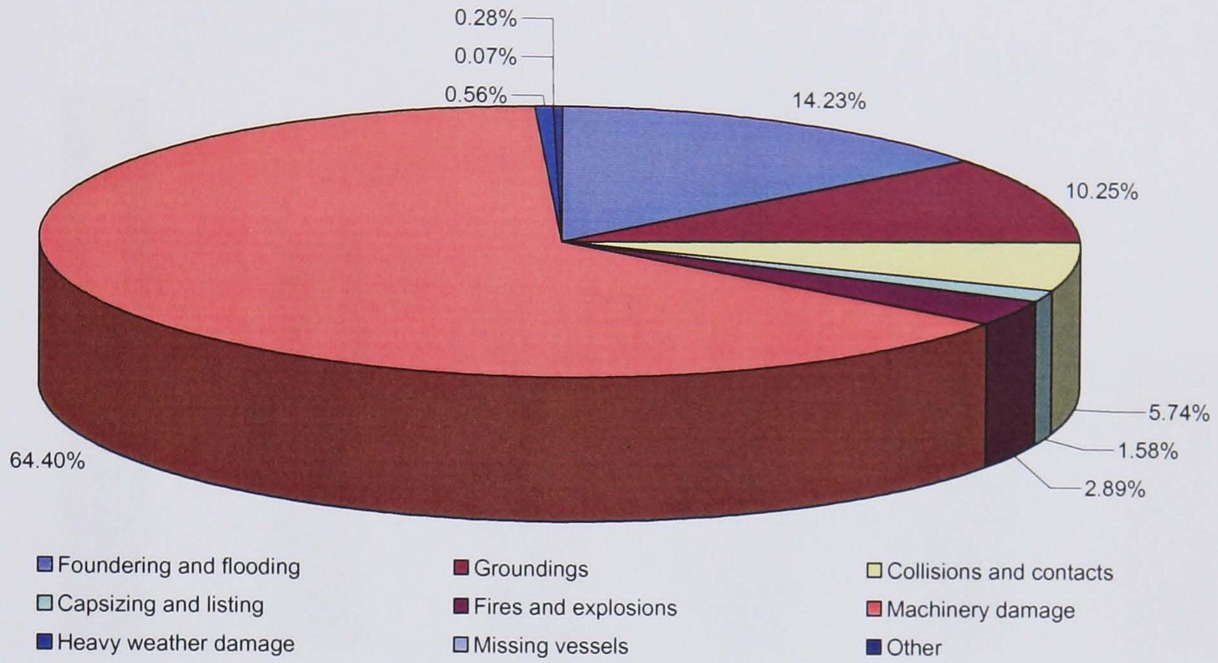


Figure 2.6 Accidents by nature (1994 - 1999)

To determine the severity of the accidents on fishing vessels, data reflecting the accident to vessel crew together with the number of deaths that resulted are gathered and presented in figures 2.7 and 2.8. These bar charts show that almost 30% of accidents to crew on vessels that are under 12 meter result in deaths and for vessels that are 12-24 meters and more than 24 meters in length, these figures are calculated to be 13% and 15% respectively. The results indicate that vessels under 12 meters have the highest casualty rates and suffer severe consequences when an accident happens. This could be attributed to the size and stability of these vessels when sailing in bad weather conditions. The number of under 12 meter vessels that were lost is much higher than the other vessels as seen in figure 2.9. The trend in the number of vessels lost is difficult to determine, as it does not follow any specific mathematical rule. However, by comparing the graphs in figures 2.1, 2.2 and 2.9, it can be concluded that from 1997, the number of vessels lost is generally increasing as the number of registered vessels is decreasing.

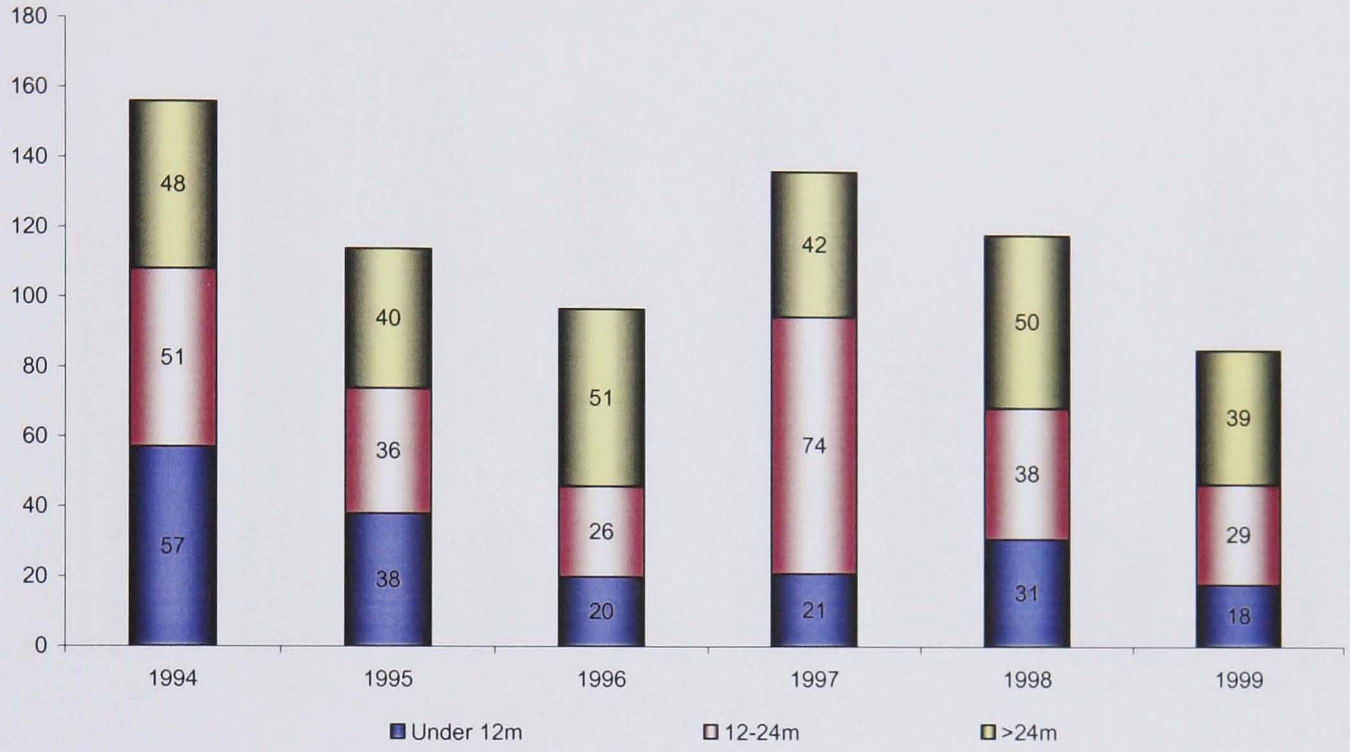


Figure 2.7 Accidents to crew

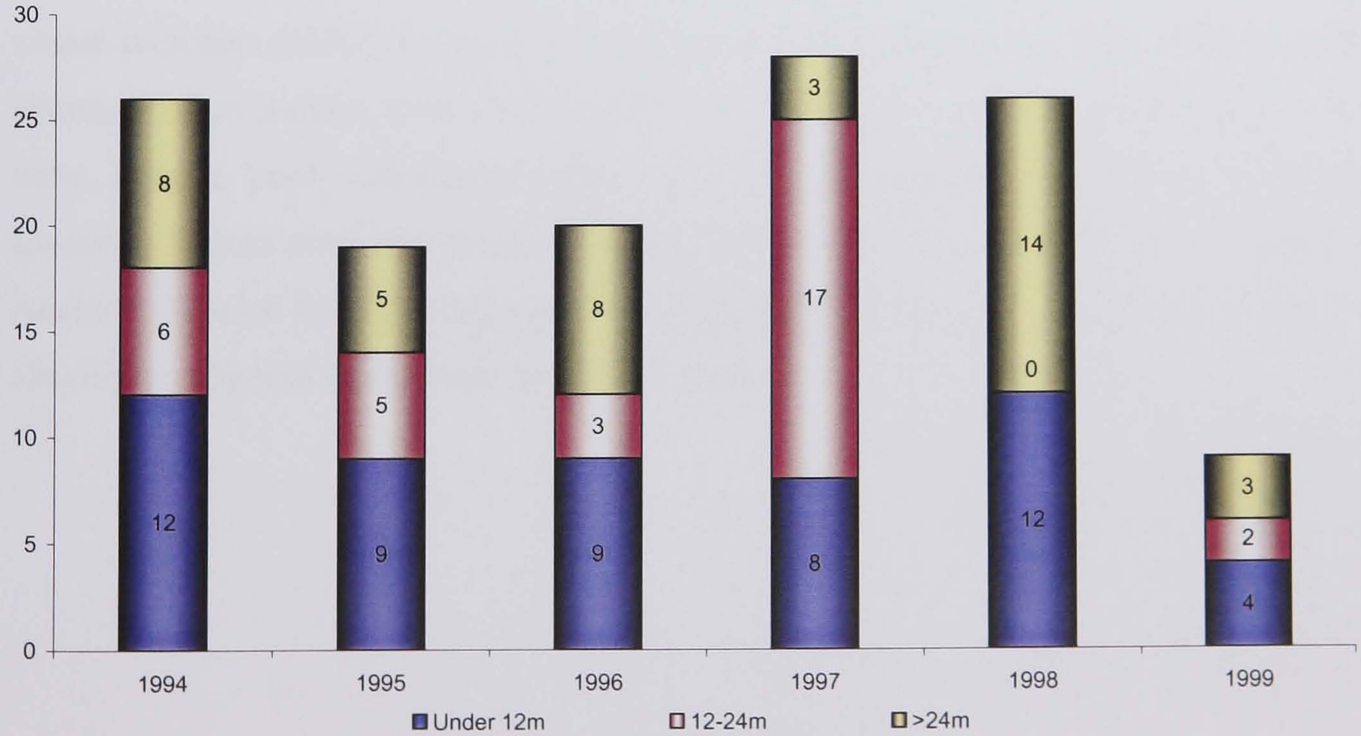


Figure 2.8 Deaths to crew

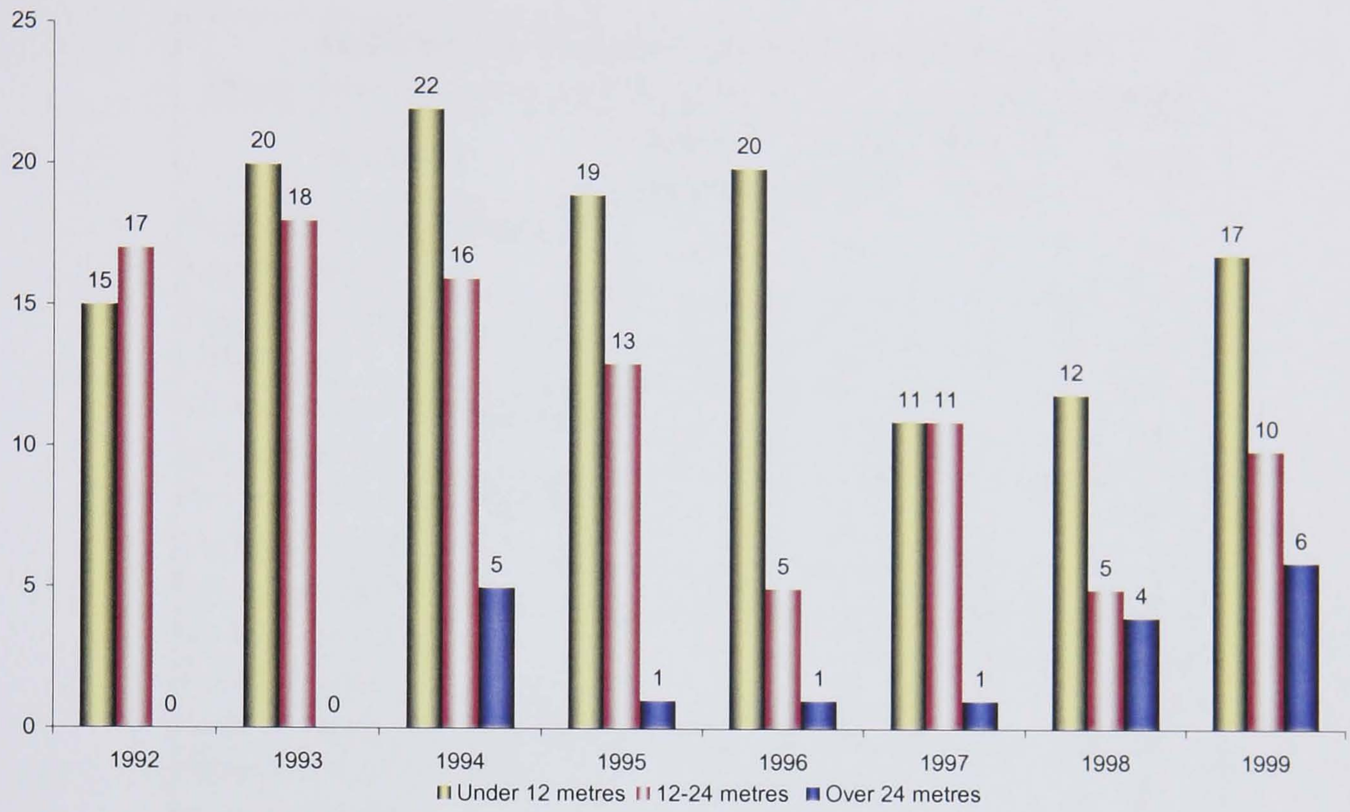


Figure 2.9 Vessels lost

Table 2.1 gives the detailed breakdown of accidents by vessel length and accident cause for 1999 [MAIB 1999a]. From this table, it is noted that a great proportion of fishing vessel accidents (20%) is caused by negligence/carelessness of the crew. This could be summarised as human error attributed by several factors including competency of the crew, fatigue, poor manning of vessel and difficult operating conditions. A method assessing human error and means to reduce these errors will be described in chapter 8. Accidents caused by the lifting gear (15%) and other fishing gear equipment (12%) are also high compared to the other accident causes.

Accidents by Vessel Length and Accident Cause (more than one cause may be applicable to a particular accident)				
Accident	*Under 12 metres*	*12-24 metres*	*Over 24 metres*	*Total*
Negligence/carelessness of injured person	4	10	9	23
Ship movement	1	3	3	7
Lifting gear	2	8	7	17
Miscellaneous fishing gear and equipment	3	5	6	14
Failure of deck machinery and equipment	-	2	5	7
Sea washing inboard	3	1	4	8
No known cause	2	-	2	4
Trawl boards	-	1	4	5
Door or hatch not secured	1	1	-	2
Failure to comply with warnings/orders	-	1	-	1
Unsecured non-fishing gear on deck	-	-	-	-
Unfenced opening	1	-	-	1
Fatigue	-	-	-	-
Failure to use protective clothing or equipment	3	1	1	5
Slippery surface	-	-	3	3
Lifting/carrying by hand incorrectly	-	-	3	3
Failure of engine room and workshop equipment	-	-	-	-
Other	2	5	4	11

Table 2.1 Accidents by Vessel Length and Accident Cause

2.5 Data Analysis

In many cases of fishing vessel accidents, information is incomplete or totally lacking. This makes it difficult to analyse the events that lead to the accident. Accurate historical and current data on vessels, fishermen, professional experience, hours and nature of exposure and safety performance of personnel and equipment are fundamental to assessing safety problems, monitoring results of safety programmes and measuring the effectiveness of safety improvement strategies [Loughran C.G. et. al., 2001]. Very few data are regularly collected or published on these parameters. The limited data makes it difficult to quantify safety problems, determine casual relations and assess safety improvement strategies. However, the data that are available indicate that significant safety problems exist and that human error, vessels and equipment inadequacies and environmental conditions all contribute to them.

Marine accidents that have occurred could have been prevented with greater attention to safety. This is particularly true for fishing vessels. Recent inquiries into the losses of fishing vessels "Pescado" [MAIB, 1998] and "Magaretha Maria" [MAIB, 1999b] have raised concerns as to how similar accidents may be prevented in the future. The data analysis in section 2.4 shows that there is a rise of fishing vessel accidents and the trend seems to be continuing in an upward fashion. From the literature survey, it was found that safety assessment of fishing vessels had been limited to stability consideration and very little work has been carried out on the operational and equipment safety assessment. From the data given in section 2.4, it can be deduced that fishing vessel safety needs to be addressed and the number of accidents and incidents related to the operation and equipment is to be reduced. In order to direct the attention of the safety assessment on fishing vessels, the probable causes of each accident category have been investigated and are summarised here [MAIB 1999a].

2.5.1 Machinery damage

The highest number of incidents reported in the official statistics relates to machinery damage. Although most machinery failures do not threaten the vessel or lives of the crew, given other factors such as bad weather or being in a tideway, the consequences could be disastrous. Upon investigation of several fishing vessels in the UK, it was found that maintenance activities on board these vessels were almost non-existent. This is thought to lead to the high number of machinery failures. The present situation concerning maintenance on fishing vessels is discussed in detailed in chapter 7. A method for improving the current status is proposed within the mentioned chapter.

2.5.2 Foundering/flooding

Typically these incidents are caused by burst pipes, fittings working loose, leaking glands and sprung planks. Flooding is a particular problem with smaller wooden vessels. Smaller vessels are often of clinker construction where the strakes are lapped against each other and clenched. They are reliant upon the swelling nature of the wood when soaked for making a good seal. This method of construction is particularly vulnerable in heavy sea conditions. These types of accidents can also happen on vessels that are of metal construction. Sometimes incompatible metals become rapidly corroded in a seawater environment; examples are copper piping adjacent to steel or aluminium structures, which resulted in a relatively new vessel suffering a major flooding incident [Hopper A.G. and Dean A.J., 1992].

2.5.3 Grounding

These incidents are associated with all classes of fishing vessels and can be due to various causes. Engine or gearbox failures and propeller fouled by a rope or fishing net are common causes. However, many cases have been associated with navigational error. This may be a failure to plot a proper course, failure to keep a check on vessel position with wind and tidal drift, reliance on auto-pilots and electronic plotters and a failure to keep a proper lookout. There are no requirements to carry on board a certified navigator (especially for vessels under 12 meters registered length), hence the navigators on these vessels rely heavily upon experience and 'gut feeling', which in turn could increase the level of navigator error.

2.5.4 Collisions and contacts

Almost all collision and contact incidents involve a fishing vessel and a merchant vessel and almost without exception they are due to human error. Large merchant vessels may have a poor line of sight from the wheelhouse and small fishing vessels are not easily seen under the bow. Apart from that, skippers on fishing vessels are too involved in the fishing operation to plot the position and movement of other vessels approaching them. The fishing operation itself requires sudden stopping or course changing which could lead to unavoidable collisions. Collisions and contacts could also occur involving two or more fishing vessels. This is especially true when pair trawling is in progress. However, the consequences are less severe and the incident normally occurs due to errors of judgement by one or both parties involved.

2.5.5 Fires and explosions

Investigation of these accidents have shown that in most cases the fire had originated from the engine room and are caused by oil or fuel coming into contact with hot exhausts. Other causes are heating and cooking stoves and electrical faults. There have been several cases where the fire had started in the accommodation area due to the crew smoking cigarettes in the sleeping bunk. The number of accidents caused by fire has been relatively low compared to other categories. However, due to the limited fire fighting resources on board fishing vessels, it has the potential to cause severe damage and even loss of life.

2.5.6 Capsizing

From the MAIB reports, it is evident that the majority of capsizing incidents occur during the fishing and recovery of gear operations. This shows that for the vessels that do capsize, there is an insufficient factor of safety in the present stability criteria. This insufficient factor is introduced by the act of fishing and the associated moment lever introduced by the gear along with the wind lever in the dynamic situation at sea [Loughran C.G. et. al., 2001]. This is perhaps the most lethal type of incident in terms of loss of life. The capsizing of small fishing vessels happens in a matter of minutes and this leaves little chance for the crew to escape. Extreme sea conditions are one of the many factors that lead to a capsize. As most skippers and crew depend on the catch for their daily income, skippers have been known to put their vessel through extreme sea conditions to get to a fishing ground and sometimes drift within the fishing grounds waiting for the sea to calm in order to resume fishing operations. However, the most common cause of capsizing is when the fishing gear becomes snagged. Trawl gear fouled on some sea bed obstruction is a commonplace happening for a fishing skipper. Attempts to free badly fouled gear by heaving on the winch can result in forces that are large enough to roll the vessel over. Heaving on both warps at the same time will produce a balanced situation but if one side suddenly becomes free, the force on the opposite side may be sufficient to capsize the vessel.

2.5.7 Heavy weather damage

The number of vessels suffering weather damage is comparatively low as seen in the graph in figure 2.5. Small vessels are particularly vulnerable to these accidents, especially when they go out further away from the coastline for their fishing operation (due to the reduced fishing opportunities in British waters). These small vessels will be working far offshore where they cannot withstand the severe weather and wave conditions that can occur unexpectedly. Heavy weather can weaken the hull structure of the vessel and at the same time, cause deck fittings to come loose and lead to an accident.

2.6 Conclusion

A review has been performed on available incident data relevant to fishing vessels. It was found that the amount of data relating to this type of vessels is limited. The only data source that compiles fishing vessel accident/incident data has been identified to be the MAIB. Over the years, the database maintained by the MAIB has considerably improved in terms of its format. However, the database still lacks information about the casual relationship between the causes and effects of the accidents/incidents.

Data interpretation should be carried out with caution, as it is highly likely that there is some degree of under reporting of incidents. This would entail that the actual number of deaths, accidents and vessel losses, would be much higher than the figures presented here. However, the data gathered and analysed in this chapter show that there is a real problem in the fishing vessel industry. The frequency of accidents and the associated severity is still high for maritime standards, and the number of accidents/incidents has to be reduced.

The work in this thesis attempts to provide assessment methods that could identify the high-risk areas on a fishing vessel and thereby justifying the cost of implementing risk management solutions. It can be concluded that due to the lack of proper reporting of accidents/incidents on fishing vessels, subjective methods of risk and safety analysis would be more favourable. As such, the methods developed and presented in the following chapters are able to handle vague and imprecise data.

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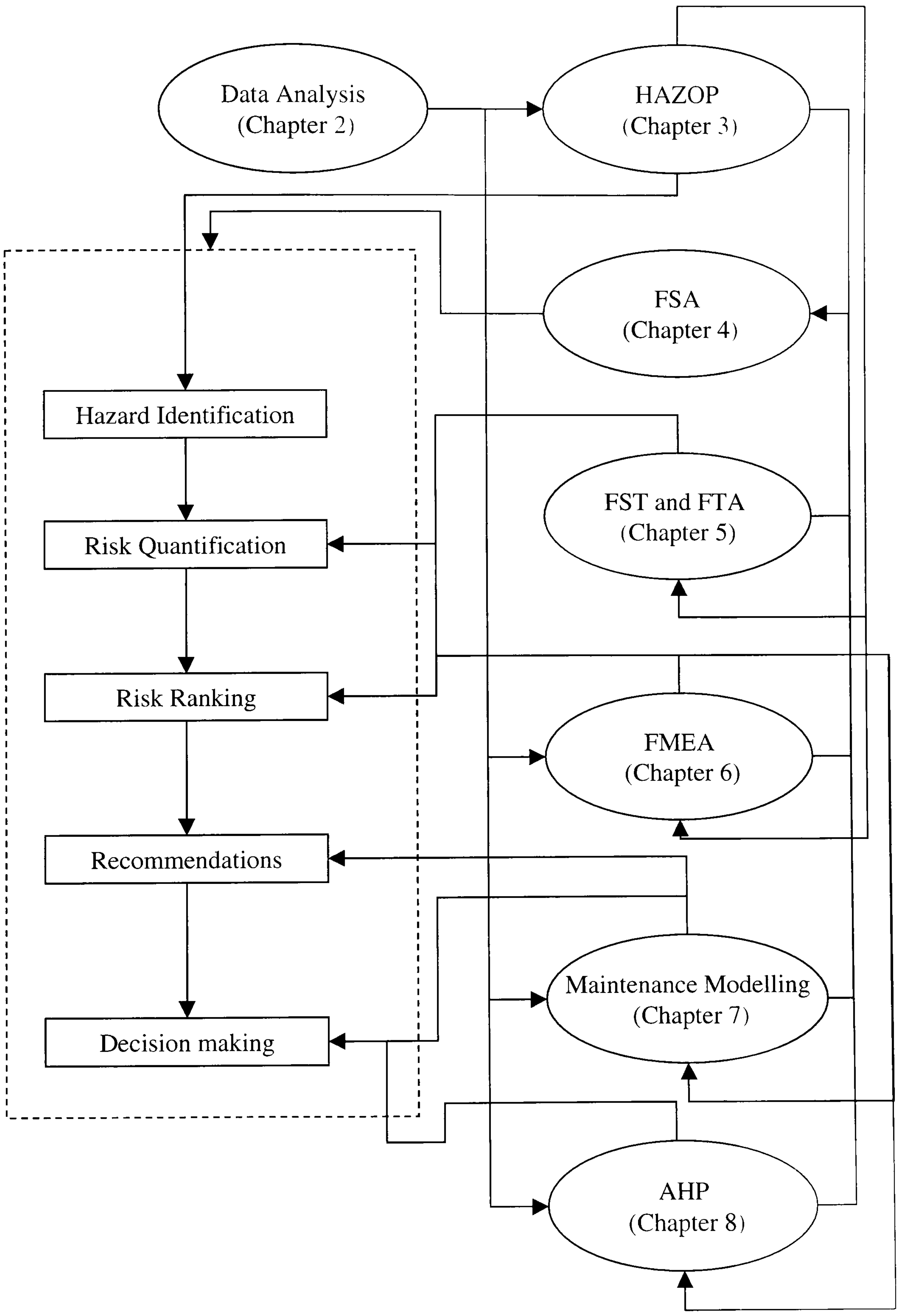

Figure 1 Structure of the thesis

CHAPTER 3

SAFETY ANALYSIS TECHNIQUES

Summary

This chapter gives an introduction to common safety analysis techniques and provides a detailed review of some of the typical methods employed in the industry today. A detailed discussion is carried out on HAZard and OPerability studies (HAZOP) and this is followed by a proposed approach using HAZOP to identify hazards on board fishing vessels. Advantages and disadvantages of the safety analysis techniques described are discussed.

3.1 Introduction

Reliability and safety analyses are different concepts that have a certain amount of overlapping between them. Reliability analysis of an item involves studying its characteristics expressed by the probability that it will perform a required function under stated conditions for a stated period of time. If such an analysis is extended to involve the study of the consequences of the failures in terms of possible damage to property and the environment or injury/death of people, the study is referred to as safety analysis.

Risk is defined as the product of the probability of occurrence, the associated consequences and the likelihood of consequences of an accident. Safety is the ability of an entity not to cause, under given conditions, critical or catastrophic consequences. It is generally measured by the probability that an entity, under given conditions, will not cause critical or catastrophic events [Villemuer A., 1992].

Safety assessment is a logical and systematic way to seek answers to a number of questions about the system under consideration. The assessment of risk associated with an engineering system or product may be summarised to answer the following three questions:

1) What can go wrong?
2) What are the effects and consequences?
3) How often will they happen?

The answer obtained from these questions will provide the information about the safety of the system. Such information is interesting but is of no practical significance unless there is a method for controlling and managing the risk levels of specific hazards to tolerable levels. Hence, a complete safety assessment will require a fourth question to be answered:

4) What measures need to be undertaken to reduce the risks and how can this be achieved?

Safety analysis can be generally divided into two broad categories, namely, quantitative and qualitative analysis methods. Depending on the safety data available to the analyst, either a quantitative or a qualitative safety analysis can be carried out to study the risk of a system in terms of the probability of occurrence of each hazard and possible consequences of the accident.

3.2 Qualitative Safety Analysis

Qualitative safety analysis is used to locate possible hazards and to identify proper precautions that will reduce the frequencies or consequences of such hazards. Generally this technique aims to generate a list of potential failures that affect the system under consideration. Since this method does not require failure data as an input to the analysis, it relies heavily on engineering judgement and past experience.

A common method employed in qualitative safety analysis is the use of a risk matrix method [Halebsky M., 1989; Tummala V.M.R. and Leung Y.H., 1995]. The two parameters that are considered are the likelihood of occurrence of the failure event and the severity of the consequences of the failure event. Upon identifying all the hazards within the system under consideration, each hazard is evaluated for these two parameters. The severity of all the failure events could be assessed in terms of four categories as shown in table 3.1 [Military Standard, 1993].

Hazard Consequences	Hazard severity	Category
Death, system loss or severe environmental damage, etc	Catastrophic	1
Severe injury or major system or environmental damage, etc	Critical	2
Minor injury or minor system or environmental damage, etc	Marginal	3
Less than minor injury or less than minor system or environmental damage, etc	Negligible	4

Table 3.1 Assessment of hazard severity and categories.

The likelihood of occurrence is assessed qualitatively as frequent, probable, occasional, remote or improbable as depicted in table 3.2 [Military Standard, 1993]. Each of these categories can be represented quantitatively by a range of probabilities as seen in column three of table 3.2. This is to provide a rough guideline for the experts or analysts who are providing the information or carrying out the analysis.

Hazard Categories	Qualitative	Quantitative	Level
Frequent	Likely to occur frequently	The probability is greater than 10^{-1}	A
Probable	Will occur several times in the life time of an item	The probability is between 10^{-2} and 10^{-1}	B
Occasional	Likely to occur sometime in the life of an item	The probability is between 10^{-3} and 10^{-2}	C
Remote	Unlikely but possible to occur in the lifetime of an item	The probability is between 10^{-6} and 10^{-3}	D
Improbable	So unlikely, it can be assumed occurrence may not be experienced	The probability is less than 10^{-6}	E

Table 3.2 Assessment of hazard probabilities and levels

It is reasonable to assign a high priority if the hazard has a catastrophic consequence and a frequent probability. On the other hand, it is also reasonable to assign a low priority if the hazard has a negligible consequence and improbable probability. Based on this logic, certain acceptable criteria can be developed. All identified hazards can be prioritised corresponding to safety and reliability objectives by appropriate hazard indexes using the hazard severity and the corresponding hazard probabilities as shown in table 3.3 [Military Standard, 1980]. The hazard probabilities shown in this table is used to carry out qualitative analysis for a military defence system. These probabilities can be assigned appropriately when different systems are considered. If an identified hazard is assigned with a hazard index of 1A, 1B, 1C, 2A, 2B or 3A, it needs an immediate corrective action. A hazard with an index 1D, 2C, 2D, 3B or 3C would require a possible corrective action. Similarly, a hazard with index 1E, 2E, 3D, 4A or 4B would be tracked for a corrective action with low priority; or it may not warrant any corrective action. On the other hand, a hazard with index 4C, 4D or 4E might not even require a review for action.

All the identified hazards within the system under study can be evaluated using this method to produce a risk ranking based on the highest priority down to the lowest priority. A variation of this qualitative risk matrix approach will be presented in chapter 4 with its application demonstrated for the safety analysis of a fishing vessel.

Hazard probability	**Hazard Severity**			
	Catastrophic	Critical	Marginal	Negligible
(A) Frequent ($x > 10^{-1}$)	1A	2A	3A	4A
(B) Probable ($10^{-1} > x > 10^{-2}$)	1B	2B	3B	4B
(C) Occasional ($10^{-2} > x > 10^{-3}$)	1C	2C	3C	4C
(D) Remote ($10^{-3} > x > 10^{-6}$)	1D	2D	3D	4D
(E) Improbable ($x < 10^{-6}$)	1E	2E	3E	4E

Table 3.3 Priority matrix based on hazard severity and hazard probability

3.3 Quantitative Safety Analysis

Quantitative safety analysis utilises what is known and assumed about the failure characteristics of each individual component to build a mathematical model that is associated with some or all of the following information:

- Failure rates.
- Repair rates.
- Mission time.
- System logic.
- Maintenance schedules.
- Human error.

Similar to the qualitative analysis, the probability of occurrence of each system failure event and the magnitude of possible consequences are to be obtained. However, these parameters are to be quantified.

3.3.1 Event probabilities

There are predominantly three methods that could be used to determine the probability of occurrence of an event, namely [Preyssl C., 1995]:

1. Statistical method.
2. Extrapolation method.
3. Expert judgement method.

The statistical method involves the treatment of directly relevant test of experience data and the calculation of the priori probabilities. The extrapolation method involves the use of model prediction, similarity considerations and Bayesian concepts. Limited use of expert judgement is made to estimate unknown values as input to the extrapolation method. The expert judgement method involves direct estimation of probabilities by specialists.

These methods can be used together in an effective way to produce a reasonable estimate of the probability of an event occurring. The flowchart in figure 3.1 shows the type of event probability produced depending on the available data.

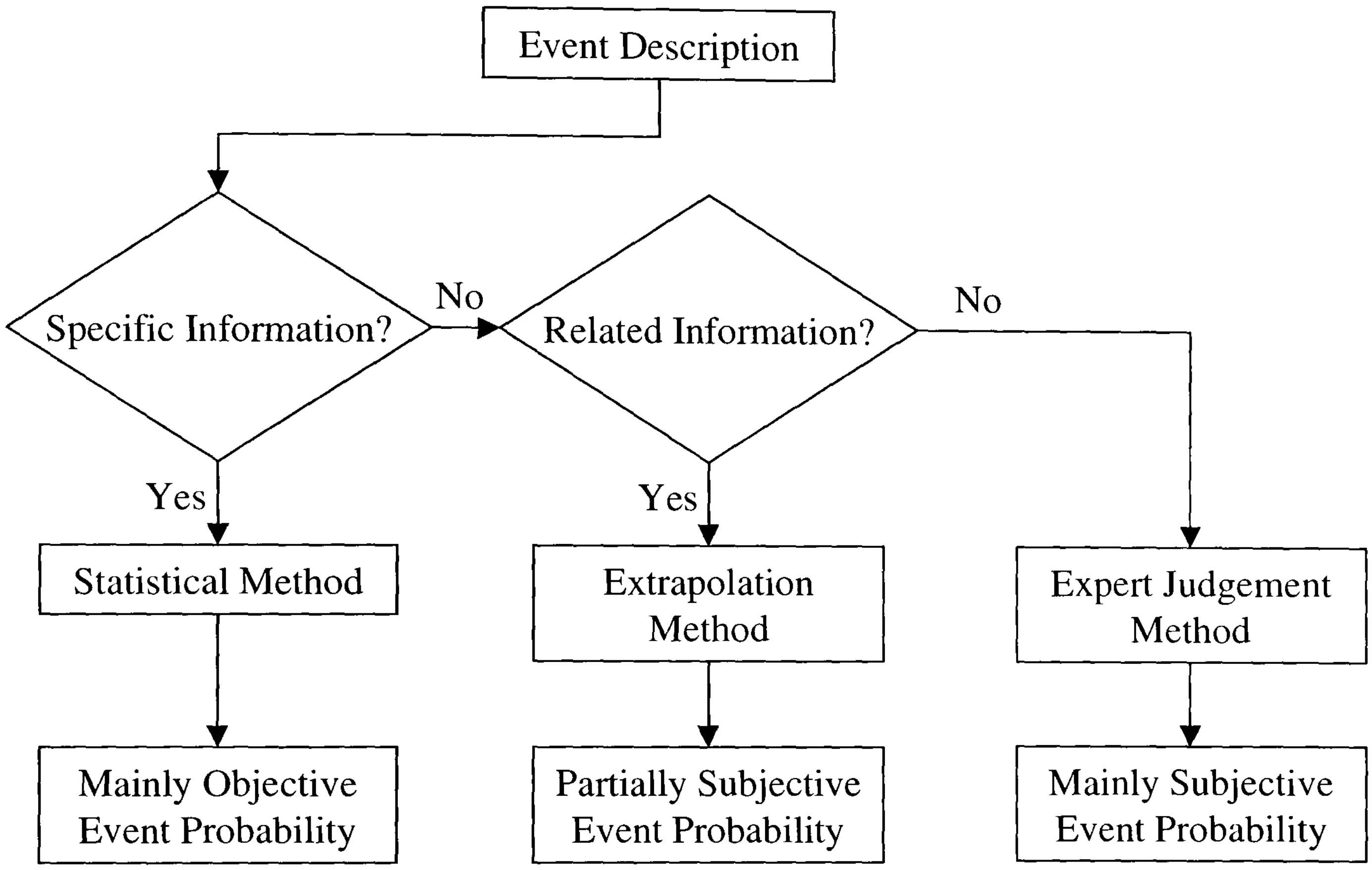

Figure 3.1 Event probability determination

3.3.2 Event Consequences

The possible consequences of a system failure event can be quantified in terms of the possible loss of lives and property damage, and the degradation of the environment caused by the occurrence of the failure event [Smith D.J., 1985; Smith D.J., 1992]. Experts of the particular operating situation normally quantify these elements in monetary terms. Quantifying human life in monetary terms could be difficult as it involves several moral issues that are constantly debated. Hence, it is normally expressed in terms of the number of fatalities [Henley E.J. and Kumamoto H., 1992].

The process of risk assessment is initially performed qualitatively and later extended quantitatively to include data when it becomes available. The interactions and outcomes of both these methods are seen in figure 3.2. Using the quantified method, risk evaluation can be carried out to determine the major risk contributors and the analysis can be attenuated to include cost benefit assessment of the risk control options.

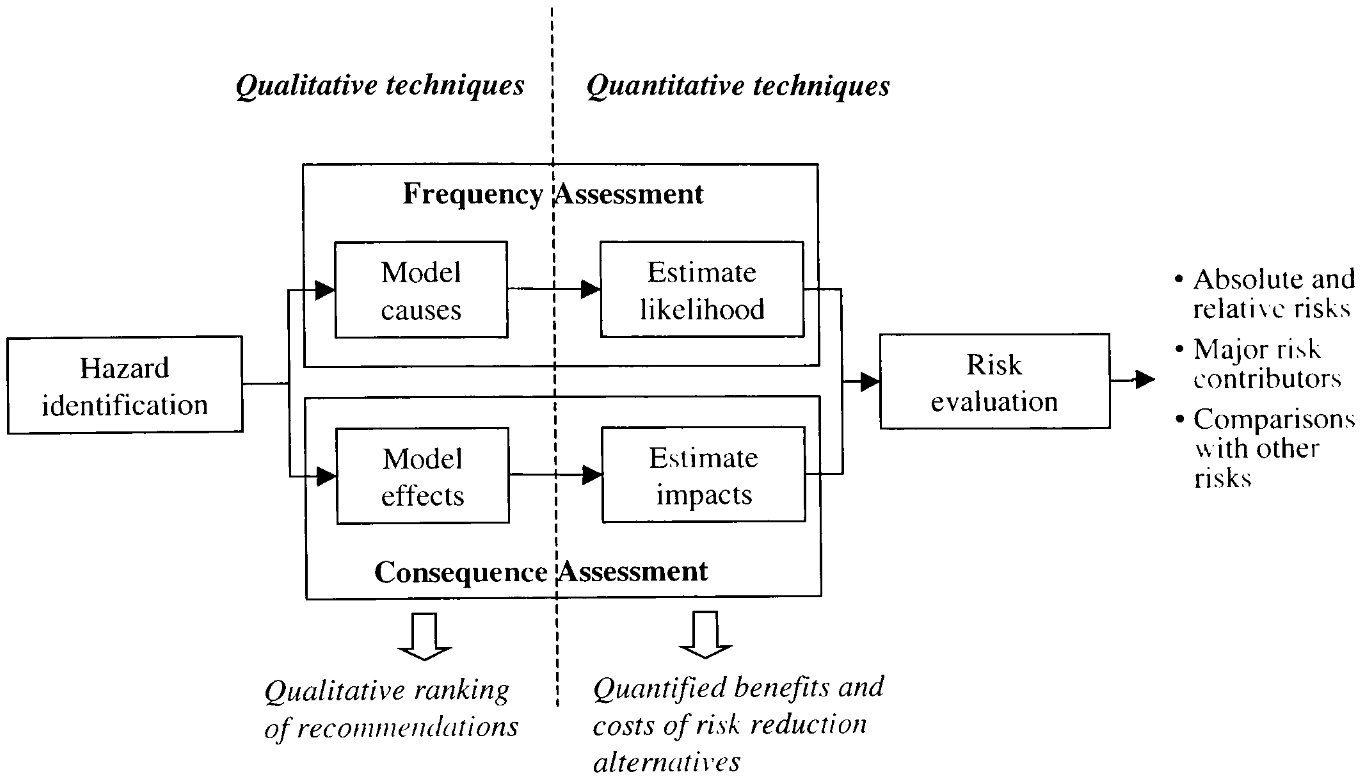

Figure 3.2 Qualitative and quantitative analysis

3.4 Cause and Effect Relationship

As discussed in sections 3.2 and 3.3, safety analysis techniques can be initially categorised either as qualitative or quantitative methods. However, the way each analysis explores the relationship between causes and effects can be categorised further into four different categories, namely,

1. Deductive techniques.
2. Inductive techniques.
3. Exploratory techniques.
4. Descriptive techniques.

Deductive techniques start from known effects to seek unknown causes, whereas inductive techniques start from known causes to forecast unknown effects. Exploratory techniques establish a link between unknown causes to unknown effects and descriptive techniques link known causes to known effects. These four ways to investigate the relationship between cause and effects are illustrated by means of a table as seen in table 3.4.

		Effects	
		Known	Unknown
Cause	Known	**Descriptive techniques**	**Inductive techniques**
	Unknown	**Deductive techniques**	**Exploratory techniques**

Table 3.4 Ways to investigate cause-effect relationship

3.5 Preliminary Hazard Analysis (PHA)

Preliminary Hazard Analysis (PHA) was introduced in 1966 after the Department of Defence of the United States of America requested safety studies to be performed at all stages of product development. The Department of Defence issued guidelines that came into force in 1969 [MIL-STD-882, 1969; MIL-STD-882D, 1999].

Preliminary Hazard Analysis is performed to identify areas of the system, which will have an effect on safety by evaluating the major hazards associated with the system. It provides an initial assessment of the identified hazards. PHA typically involves:

1) Determining hazards that might exist and possible effects.
2) Determine a clear set of guidelines and objectives to be used during a design.
3) Create plans to deal with critical hazards.
4) Assigning responsibility for hazard control (management and technical).
5) Allocate time and resources to deal with hazards.

Brainstorming techniques are used during which the design or operation of the system is discussed on the basis of the experience of the people involved in the brainstorming activity. Checklists are commonly used to assist in identifying hazards.

The results of the PHA are often presented in tabular form, which would typically include information such as but not limited to [Henley E.J. and Kumamoto H., 1992; Smith D.J., 1992; Villemuer A., 1992]:

(a) A brief description of the system and its domain.

(b) A brief description of any sub-systems identified at this phase and the boundaries between them.

(c) A list of identified hazards applicable to the system, including a description and unique reference.

(d) A list of identified accidents applicable to the system including a description, a unique reference and a description of the associated hazards and accident sequences.

(e) The accident risk classification.

(f) Preliminary probability targets for each accident.

(g) Preliminary predicted probabilities for each accident sequence.

(h) Preliminary probability targets for each hazard.

(i) A description of the system functions and safety features.

(j) A description of human error which could create or contribute to accidents.

The advantages of using the PHA method include:

- It identifies the potential for major hazards at a very early stage of project development.
- It provides basis for design and siting decisions.
- It helps to ensure plant to plant and plant to environment compatibility.
- It facilitates a full hazard analysis later.

The disadvantage of PHA is that it is not comprehensive and must be followed by a full HAZard and OPerability (HAZOP) study.

3.5.1 Subsystem Hazard Analysis/System Hazard Analysis

Subsystem Hazard Analysis (SSHA) or System Hazard Analysis (SHA) are analyses requiring detailed studies of hazards, identified in the PHA, at the subsystem and system levels, including the interface between subsystems and the environment, or by the system operating as a whole. Results of this analysis include design recommendations, changes or controls when required, and evaluation of design compliance to contracted requirements. Often subsystem and system hazards are easily recognised and remedied by design and procedural measures or controls. These hazards are often handled by updating and expanding the PHA, with timing of the SSHA/SHA normally determined by the availability of subsystem and system design data (usually begins after the preliminary design review and completed before the critical design review).

3.5.2 Operating and Support Hazard Analysis

Operating and Support Hazard Analysis (OSHA) is an analysis performed to identify those operating functions that may be inherently dangerous to test, maintenance, handling, transportation or operating personnel or in which human error could be hazardous to equipment or people. The information for this analysis is normally obtained from the PHA. The OSHA should be performed at the point in system development when sufficient data is available, after procedures have been developed. It documents and evaluates hazards resulting from the implementation of operations performed by personnel. It also considers:

- The planned system configuration at each phase of activity.
- The facility interfaces.
- The planned environments.
- The support tools or other equipment specified for use.
- The operation or task sequence.
- Concurrent task effects and limitations.
- Regulatory or contractually specified personnel safety and health requirements.
- The potential for unplanned events including hazards introduced by human error.

OSHA identifies the safety requirements (or alternatives) needed to eliminate identified hazards or to reduce the associated risk to an acceptable level.

3.6 What-If Analysis

What-If analysis uses a creative team brainstorming "what if" questioning approach to the examination of a process to identify potential hazards and their consequences.

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Hazards are identified, existing safeguards noted, and qualitative severity and likelihood ratings are assigned to aid in risk management decision making. Questions that begin with "what-if" are formulated by engineering personnel experienced in the process or operation preferably in advance.

There are several advantages and disadvantages to using the What-If technique. The advantages include:

- Team of relevant experts extends knowledge and creativity pool.
- Easy to use.
- Ability to focus on specific element (i.e. human error or environmental issues).

The disadvantages include:

- Quality is dependent on knowledge, thoroughness and experience of team.
- Loose structure that can let hazards slip through.
- Does not directly address operability problems.

3.7 Hazard and Operability Studies

A HAZard and OPerability (HAZOP) study is an inductive technique, which is an extended Failure Mode, Effects and Criticality Assessment (FMECA). The HAZOP process is based on the principle that a team-approach to hazard analysis will identify more problems than when, individuals working separately combine results.

The HAZOP team is made up of individuals with varying backgrounds and expertise. The expertise is brought together during HAZOP sessions and through a collective brainstorming effort that stimulates creativity and new ideas, a thorough review of the process under consideration is made. In short it can be applied by a multidisciplinary team using a checklist to stimulate systematic thinking for identifying potential hazards and operability problems, particularly in the process industries [Bendixen L.M. et. al., 1984].

The HAZOP team focuses on specific portions of the process called "nodes". A process parameter (e.g. flow) is identified and an intention is created for the node under consideration. Then a series of guidewords is combined with the parameter "flow" to create a deviation. For example, the guideword "no" is combined with the parameter "flow" to give the deviation "no flow". The team then focuses on listing all the credible causes of a "no flow" deviation beginning with the cause that can result in the worst possible consequence the team can think of at the time. Once the causes are recorded, the team lists the consequences, safeguards and any recommendations deemed appropriate. The process is repeated for the next deviation and so on until completion of the node. The team moves on to the next node and repeats the process.

3.7.1 Guidewords, selection of parameters and deviations

The HAZOP process creates deviations from the process design intent by combining guidewords (no, more, less, etc.) with process parameters resulting in a possible deviation from the design intent. It should be pointed out that not all guideword/parameter combinations would be meaningful. A sample list of guidewords is given below:

- No
- More
- Less
- As Well As
- Reverse
- Other Than

The application of parameters will depend on the type of process being considered, the equipment in the process and the process intent. The most common specific parameters that should be considered are flow, temperature, pressure, and where appropriate, level. In almost all instances, these parameters should be evaluated for every node. The scribe shall document, without exception, the teams' comments concerning these parameters. Additionally, the node should be screened for application of the remaining specific parameters and for the list of applicable general parameters. These should be recorded only if there is a hazard or operability problem associated with the parameter. A sample set of parameters includes the following:

- Flow
- Temperature
- Pressure
- Composition
- Phase
- Level
- Relief
- Instrumentation

3.7.2 HAZOP process

A HAZOP study can be broken down into the following steps [McKelvey T.C., 1988]:

1. Define the scope of the study.
2. Select the correct analysis team.
3. Gather the information necessary to conduct a thorough and detailed study.
4. Review the normal functioning of the process.
5. Subdivide the process into logical, manageable sub-units for efficient study and confirm that the scope of the study has been correctly set.
6. Conduct a systematic review according to the established rules for the procedure being used and ensure that the study is within the special scope.
7. Document the review proceedings.
8. Follow up to ensure that all recommendations from the study are adequately addressed.

The detailed description of the methodology can be found in [Wells G.L., 1980; Bendixen L.M. et. al., 1984; McKelvey T.C., 1988; Kletz T.A., 1992].

3.7.3 HAZOP application to fishing vessels

To apply the HAZOP process for the study of a fishing vessel system, the conventional method given in section 3.7.2 is modified and can be summarised as follows:

1. Define the system scope and team selection
    - Firstly define the scope of the study and then accordingly select the appropriate team to be involved in the study

2. Describe the system
    - Describe the system in some detail. This description should clarify the intention of the system as a whole from an operational viewpoint.
    - The information generated here will help the analyst understand the system and its criticality to the safe operation of the vessel. The data will later prove to be useful when used to determine the consequences of component failure in step 5 of the approach.

3. Break it down into smaller operations for consideration and identify each component within the considered system.
    - Having attained the overall picture, break it down into its sub-operations/routines. It is difficult to see all the problems in a complex process but when each individual process is analysed on its own, the chances are that little will be missed out. Ideally, each operation should be singled out, but it is frequently more convenient to consider more than one operation at a time due to its inter-relationship and dependency.
    - The identification of each component can be achieved by first looking at historical failure data that is available and then complementing it with components identified from equipment drawings. Component failure data can be obtained from logbooks, docking reports, Chief engineers' reports and maintenance reports.

4. Determine design intention for each component that is identified.
    - At this stage, the purpose or intention of each component is ascertained. This helps to determine the functional purpose of the specific operation and shows how it relates/interacts to achieve the process intentions.

5. Apply a series of guidewords to see how that intention may be frustrated.
    - This is the heart of HAZOP. Having decided the intention of a process, this stage analyses the ways in which it can go wrong.
    - Examples of guide words are as illustrated in table 3.5.

6. For meaningful deviations from the intention, look for possible causes and likely consequences.
   - At this stage, the root of the problem is identified and the possible consequences are predicted and complemented with any historical data available. The consequences are considered for four major categories i.e. personnel, environment, equipment and operation. At this point, it is determined how the failure of a component will affect the safety and integrity of these four categories.

7. Consider possible action to remove the cause or reduce the consequences.
   - A HAZOP team usually provides ideas to remove a cause or deal with a consequence. This could be suggestion of improvements in design, operational procedure, maintenance periods and redundancy arrangements. It would be very unusual for every single one of these actions to be put into practice, but at least a rational choice could be made.

8. Reiteration
   - Consider how the improvements will affect the operation of the system and re-evaluate what can go wrong (with the improvements incorporated).

Guide words	Examples
No	No flow, no signal
Less	Less flow, less cooling
More	Excess temperature, excess pressure
Opposite	Cooling instead of heating
Also	Water as well as lubricating oil
Other	Heating instead of pumping
Early	Opening the drain valve too soon
Late	Opening the drain valve too late
Part of	Incomplete drainage

Table 3.5 Example of guidewords

These steps can be illustrated in the flowchart in figure 3.3. There are several advantages of using HAZOP to assess the safety of fishing vessels. These include:

- It is the most systematic and comprehensive PHA methodology.
- It provides greatest safety assurance.
- It can be used in conjunction with Human Error Analysis (HEA).
- It is the only PHA to address both safety/operability problems and environmental hazards.

The HAZOP process can be time consuming and costly if it is not well prepared in advance and can be tedious if it is not well facilitated. A comprehensive HAZOP study will require many experts and a considerable duration. As such the demonstration of its application has not been carried out in this project.

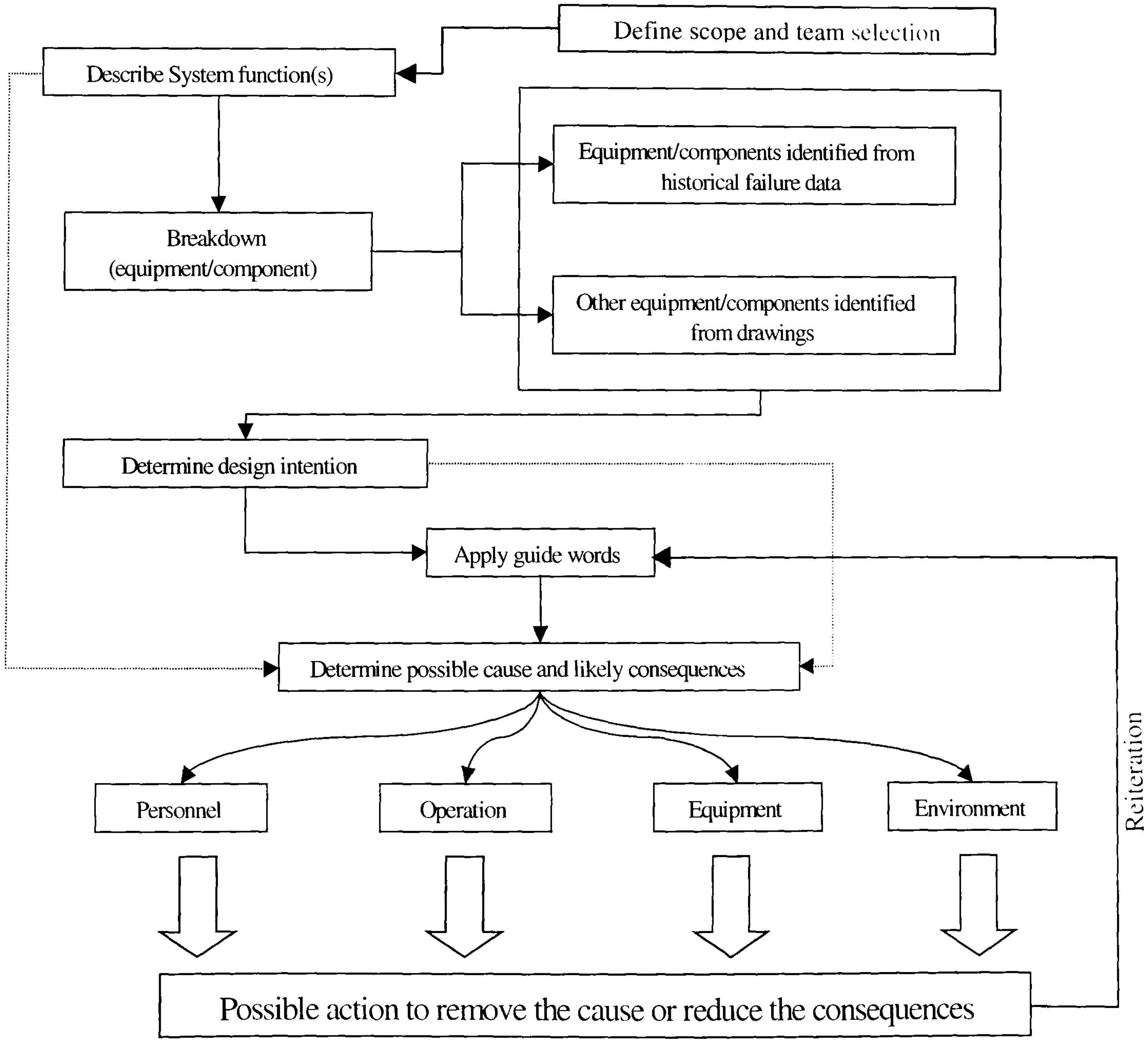

Figure 3.3 Flowchart of HAZOP process applied to fishing vessels

3.8 Fault Tree Analysis

Fault Tree Analysis (FTA) is a formal deductive procedure for determining combinations of component failures and human errors that could result in the occurrence of specified undesired events at the system level [Ang A.H.S. and Tang W.H., 1984]. It is a diagrammatic method used to evaluate the probability of an accident resulting from sequences and combinations of faults and failure events. This method can be used to analyse the vast majority of industrial system reliability problems. FTA is based on the idea that:

- A failure in a system can trigger other consequent failures.
- A problem might be traced backwards to its root causes.

The identified failures can be arranged in a tree structure in such a way that their relationships can be characterised and evaluated.

3.8.1 Benefits to be gained from FTA

There are several benefits of employing FTA for use as a safety assessment tool, such as:

- The Fault Tree (FT) construction focuses the attention of the analyst on one particular undesired system failure mode, which is usually identified as the most critical with respect to the desired function [Andrews J.D. and Moss T.R., 1993].
- The FT diagram can be used to help communicate the results of the analysis to peers, supervisors and subordinates. It is particularly useful in multi-disciplinary teams with the numerical performance measures.
- Qualitative analysis often reveals the most important system features.
- Using component failure data, the FT can be quantified.
- The qualitative and quantitative results together provide the decision-makers with an objective means of measuring the adequacy of the system design.

A FT describes an accident model, which interprets the relation between malfunction of components and observed symptoms. Thus the FT is useful for understanding logically the mode of occurrence of an accident. Furthermore, given the failure probabilities of system component, the probability of a top event occurring can be calculated. A FTA consists of the following:

- System description.
- Fault tree construction.
- Qualitative analysis.
- Quantitative analysis.

These steps are illustrated in figure 3.4.

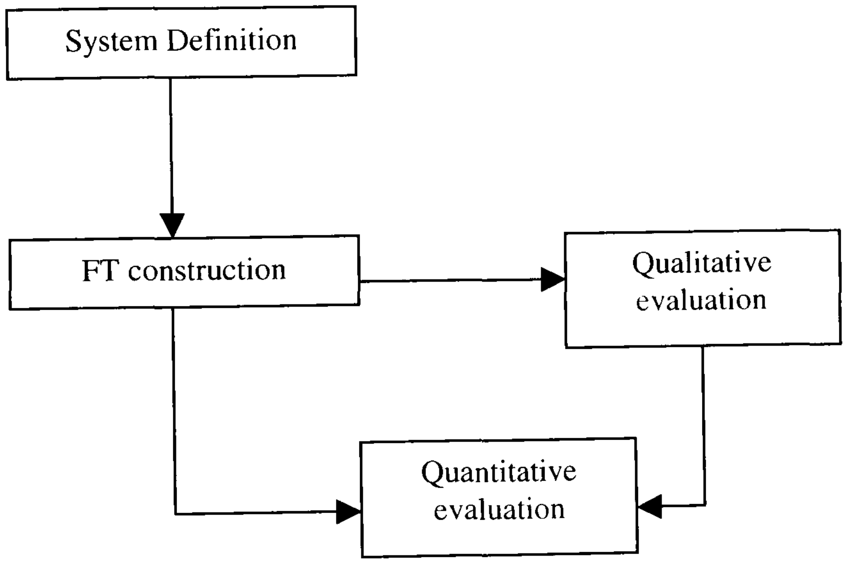

Figure 3.4 FTA method

3.8.2 System definition

FTA begins with the statement of an undesired event, e.g. failed state of a system. To perform a meaningful analysis, the following three basic types of system information are usually needed:

1. Component operating and failure modes: A description of how the output states of each component are influenced by the input states and internal operational modes of the component.

2. System chart: A description of how the components are interconnected. A functional layout diagram of the system must show all functional interconnections and identify each component.
3. System boundary conditions: These define the situation for which the fault tree is to be drawn.

3.8.3 Fault Tree construction.

FT construction, which is the first step for a failure analysis of a technical system, is generally a complicated and time-consuming task. A FT is a logical diagram constructed by deductively developing a specific system failure, through branching intermediate fault events until a primary event is reached. Two categories of graphic symbols are used in a FT construction, logic symbols and event symbols.

The logic symbols or logic gates are necessary to interconnect the events. The most frequently used logic gates in the fault tree are the **AND** and **OR** gates. The **AND** gate produces an output if all input events occur simultaneously. The **OR** gate yields output events if one or more of the input events are present.

The event symbols are rectangle, circle, diamond and triangle. The rectangle represents a fault output event, which results from combination of basic faults, and/or intermediate events acting through the logic gates. The circle is used to designate a primary or basic fault event. The diamond describes fault inputs that are not a basic event but considered as a basic fault input since the cause of the fault has not been further developed due to lack of information. The triangle is not strictly an event symbol but traditionally classified as such to indicate a transfer from one part of a FT to another. Figure 3.5 gives an example of a fault tree identifying the basic, intermediate and top event of a failure.

To complete the construction of a fault tree for a complicated system, it is necessary first to understand how the system works. This can be achieved by studying the blue prints of the system (which will reflect the interconnections of components within the system). In practice, all basic events are taken to be statistically independent unless they are common cause failures. Construction of a FT is very susceptible to the subjectivity of the analyst. Some analyst may perceive the logical relationships between the top event and the basic events of a system differently. Therefore, once the construction of the tree has been completed, it should be reviewed for accuracy, completeness and checked for omission and oversight. This validation process is essential to produce a more useful FT by which system weakness and strength can be identified.

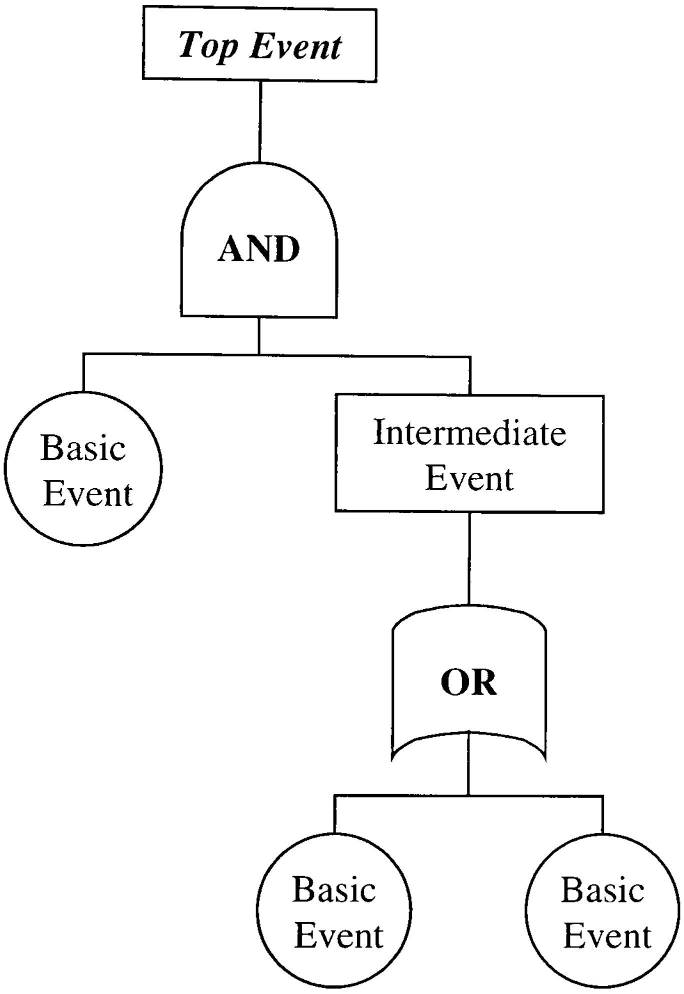

Figure 3.5 Fault tree example

3.8.4 Qualitative fault tree evaluation

Qualitative FTA consists of determining the minimal cut sets and common cause failures. The qualitative analysis reduces the FT to a logically equivalent form, by using Boolean algebra, in terms of the specific combination of basic events sufficient for the undesired top event to occur [Henley E.J. and Kumamoto H., 1992]. In this case each combination would be a critical set for the undesired event. The relevance of these sets must be carefully weighted and major emphasis placed on those of greatest significance.

3.8.5 Quantitative fault tree evaluation

In the event that the FT for a top event, T, contains independent basic events, which appear only once in the tree structure, then the top event probability can be obtained by working the basic event probabilities up through the tree. In doing so, the intermediate gate event probabilities are calculated starting at the base of the tree and working upwards until the top event probability is obtained.

When trees with repeated events are to be analysed, this method is not appropriate since intermediate gate events will no longer occur independently. If this method is used, it is entirely dependent upon the tree structure whether an overestimate or an underestimate of the top event probability is obtained. Hence, it is better to use the minimal cut-set method.

FTA may be carried out in the hazard identification and risk estimation phases of the safety assessment of fishing vessels to identify the minimal cut sets associated with serious system top events and to assess the probability of occurrence of each top event. However, due to the nature of the data available, the conventional FTA method may not be well suited for such an application. As such, a new modified method incorporating FTA and Fuzzy Set Theory (FST) will be presented and discussed in detail in chapter 5.

3.9 Event Tree Analysis

In the case of standby systems and in particular, safety and mission-oriented systems, the Event Tree Analysis (ETA) is used to identify the various possible outcomes of the system following a given initiating event which is generally an unsatisfactory operating event or situation. In the case of continuously operated systems, these events can occur (i.e. components can fail) in any arbitrary order. In the ETA, the components can be considered in any order since they do not operate chronologically with respect to each other. ETA provides a systematic and logical approach to identify consequences and to assess the probability of occurrence of each possible resulting sequence caused by the initiating failure event [Henley E.J. and Kumamoto H., 1992; Villemuer A., 1992].

3.9.1 Event tree example

A simple example of an event tree is shown in figure 3.6. This event tree is constructed to analyse the possible outcomes of a system fire. The system has two components designed to handle this event: a sprinkler system and an automated call to the fire department. If the fire department is not notified, the fire will be mostly contained by the sprinkler system. If the sprinkler system fails as well, the system will be destroyed.

ETA has proved to be a useful tool for major accident risk assessments and was used by the UK Health and Safety Executive for the assessment of risks to the public from serious accidents at installations in the Canvey Island area of Essex [Institution of Electrical Engineers (IEE), 1999]. Such an analysis can be effectively integrated into the hazard identification and estimation phases of a safety assessment programme. However, an event tree grows in width exponentially and as a result it can only be applied effectively to small sets of components.

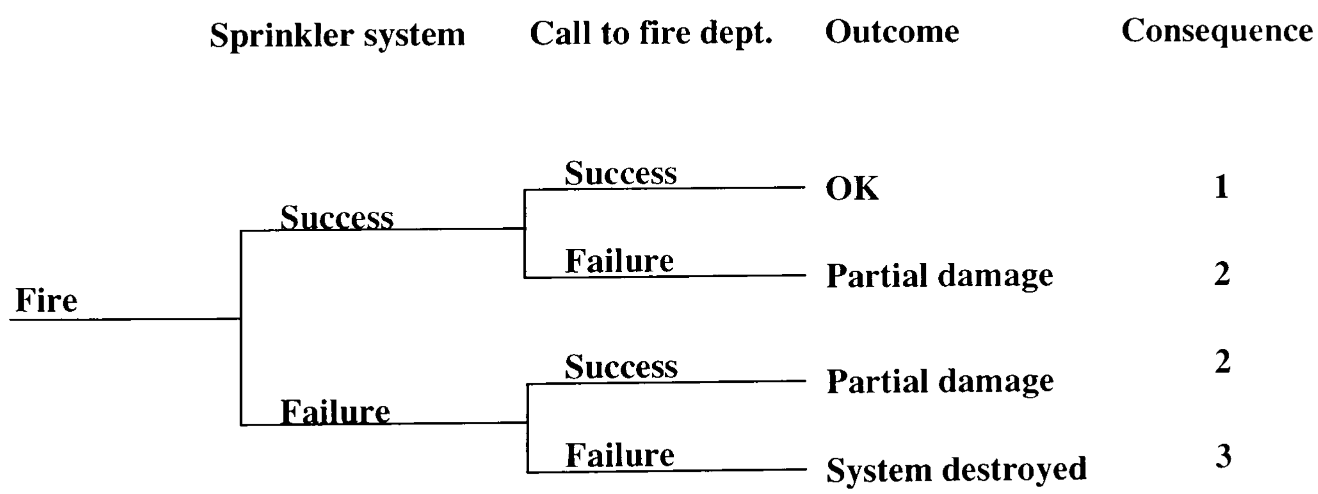

Figure 3.6 Example of an event tree

3.10 Markov Chains

Markov methods are useful for evaluating components with multiple states, for example normal, degraded and critical states [Norris J.R., 1998]. Consider the system in figure 3.7 with three possible states, 0,1 and 2 with failure rate, λ and repair rate, μ. In the Markovian model, each transition between states is characterised by a transition rate, which could be expressed as the failure rate, repair rate, etc. If it is defined that:

$P_i\,(t)$ = probability that the system is in state i at time t.

$\rho_{ij}\,(t)$ = the transition rate from state i to state j.

and if it is assumed that $P_i\,(t)$ is differentiable, it can be shown that:

$$\frac{dP_i(t)}{dt} = \left(\sum_j \rho_{ij}(t)\right) \bullet P_i(t) + \left(\sum_j \rho_{ij}(t) \bullet P_j(t)\right)$$

If a differential equation is written for each state and the resulting set of differential equation is solved, the time dependent probability of the system being in each state is obtained [Modarres M., 1993]. Markov chains are mainly a quantitative technique, however, using the state and transition diagrams, qualitative information about the system can be gathered.

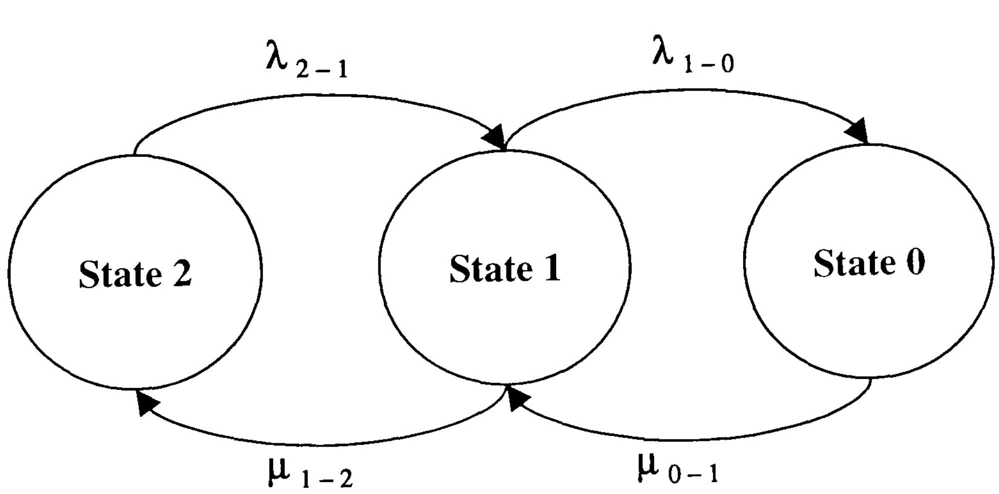

Figure 3.7 Markovian model for a system with three states

3.11 Failure Mode and Effects Analysis (FMEA)

The process of conducting a Failure Mode and Effects Analysis (FMEA) can be examined in two levels of detail. FMEA is the first level of analysis, which consists of the identification of potential failures and the effects on systems performance by identifying the potential severity of the effect. The second level of analysis is the Failure Mode, Effects and Criticality Analysis (FMECA) consisting of additional steps for calculating the risk of each failure through measurements of the severity and probability of a failure effect. Both of these methods are intended to provide information for making risk management decisions.

FMEA is an inductive process that examines the effect of a single point failure on the overall performance of a system through a "bottom-up approach" [Andrews J. and Moss T., 1993]. This analysis should be performed iteratively in all stages of design and operation of a system.

The first step in performing a FMEA is to organise as much information as possible about the system concept, design, and operational requirements. By organising the system model, a rationale, repeatable, and systematic means to analyse the system can be achieved. One method of system modelling is the system breakdown structure model - a top down division of a system (e.g. ship, submarine, propulsion control) into functions, subsystems, and components. Block diagrams and fault-tree diagrams provide additional modelling techniques for describing the component/function relationships.

The failure mode is the manner that a failure is observed in a function, subsystem, or component [Henley E.J. and Kumamoto H., 1992; Villemuer A., 1992]. Failure modes of concern depend on the specific system, component, and operating environment. The past history of a component/system is used in addition to understanding the functional requirements to determine relevant failure modes. For example, several common failure modes include complete loss of function, uncontrolled output, and premature/late operation [International Maritime Organisation, 1995].

The cause of a failure mode is the physical or chemical processes, design defects, quality defects, part misapplication, or other methods, which are the reasons for failure [Military Standards, 1980]. It is important to note that more than one failure cause is possible for a failure mode; all potential causes of failure modes should be identified, including human error.

The failure effect is the severity of the consequence of the failure mode. The effect should consider conditions that influence the system performance goals of management; for regulation, the aspect of safety is most important. The effects are generally classified into three levels of propagation: local, next higher level, and end effect. The effects should be examined at different system levels in order to determine possible corrective measures for the failure [Military Standards, 1980]. The consequences of the failure mode can be identified by a severity index indicating the relative importance of the effect due to a failure mode. Some common severity classifications include I- catastrophic, II- critical, III- major, IV- minor [International Maritime Organisation, 1995].

Part of the risk management portion of the FMEA is the determination of failure detection sensing methods and possible corrective actions [Modarres M., 1993]. There are many possible sensing device alternatives such as alarms, gauges, and inspections. An attempt should be made to correct a failure or provide a backup system (redundancy) to reduce the effects propagation to rest of system. If this is not possible, procedures should be developed for reducing the effect of the failure mode through operator actions, maintenance, and/or inspection.

FMEA/FMECA is an effective approach for risk analysis addressing risk assessment, risk management, and risk communication concerns. This analysis provides information that can be used in risk management decisions for system safety. FMEA has been used successfully within many different industries and has recently been applied in maritime regulations to address safety concerns with relatively new designs. While FMEA/FMECA is a useful tool for risk management, it also has qualities that limit its application as a complete system safety approach. This technique provides risk analysis for comparison of single component failures only; avoiding such concerns as common cause failures. Other techniques for providing risk analysis should be considered for their application to specific system safety determinations. The specific advantages and disadvantages of FMEA will be critically evaluated in chapter 6 and this is followed by a proposed modified FMEA with application for fishing vessels using fuzzy rules and grey relation theory.

3.12 Other Analysis Methods

Apart from the methods described above, several other methods have gained popularity in the industry. Many of these methods have been developed to a very advanced stage and have been integrated with other analysis tools to enhance its applicability.

3.12.1 Diagraph-based Analysis (DA)

Diagraph-based Analysis (DA) is a bottom up, event-based, qualitative technique. It is commonly used in the process industry, because relatively little information is needed to set up the diagraph [Kramer M.A. and Palowitch B.L., 1987]. In a DA, the nodes correspond to the state variables, alarm conditions or failure origins and the edges represent the casual influences between the nodes. From the constructed diagraph, the causes of a state change and the manner of the associated propagation can be found out [Umeda T. et. al., 1980]. Diagraph representation provides explicit casual relationships among variable and events of system with feedback loops. The DA method is effective when used together with HAZOP [Vaidhyanathan R. and Venkatasubramanian V., 1996]

3.12.2 Decision table method

Decision table analysis uses a logical approach that reduces the possibility of omission, which could easily occur in a fault tree construction. [Dixon P., 1964]. A decision table can be regarded as a Boolean representation model, where an engineering system is described in terms of components and their interactions. Given sufficient information about the system to be analysed, this approach can allow rapid and systematic construction of the Boolean representation models. The final system Boolean representation table contains all the possible system top events and the associated cut sets. This method is extremely useful for analysing systems with a comparatively high degree of innovation since their associated top events are usually difficult to obtain by experience, from previous accidents and incident reports of similar products, or by other means. A more detailed discussion on the use of this method for safety assessment can be found in [Wang J., 1994].

3.12.3 Limit state analysis

Limit state analysis is readily applicable to failure conditions, which result when the demand imposed on the component, or system exceeds it capability. The probability of failure is the probability the limit state functions are violated. These probabilities are estimated by the statistical analysis of the uncertainty or variability associated with the functions variables. In most cases, the analytical solution of the probability of failure is very difficult and sometimes almost practically impossible. However, by incorporating the Monte Carlo Simulation method, this setback can be addressed. This method is normally used in structural reliability predictions and represents only half of a safety assessment (as it does not consider the severity of the failure) [Bangash Y., 1983; Damkilde L. and Krenk S., 1997].

3.13 Conclusion

In this chapter, typical safety analysis methods are outlined in terms of their requirements, advantages and limitations. Some of these techniques have been successfully used in the industry and still continue to be used. However, the application of these conventional techniques to fishing vessel safety assessment may not be as straightforward as it may seem. Certain modifications are needed to enhance the application of such methods to fishing vessels. These modifications include the ability of the analysis methods to handle data that is associated with a high degree of uncertainty and the integration of expert opinion in a formal manner, where there is no bias of opinion.

The conventional methods can be used together within the framework of a Formal Safety Assessment (FSA) process. The FSA process will be described and discussed in chapter 4, detailing how the analysis methods identified here can be used effectively together with some of the novel techniques developed in the following chapters of this thesis.

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CHAPTER 5 - RISK ASSESSMENT USING FUZZY SET APPROACH

CHAPTER 6 - MODIFIED FAILURE MODE AND EFFECTS ANALYSIS

CHAPTER 4

FORMAL SAFETY ASSESSMENT

Summary

This chapter discusses the inception of Formal Safety Assessment (FSA), starting from the disaster caused by the Piper Alpha incident in 1988 and the consequent unfolding events, which led to the proposal by the Marine Coastguard Agency (MCA) to the International Maritime Organisation (IMO). Applications of FSA by the IMO for different systems are listed and referred to. An application of the FSA is proposed and demonstrated for a generic fishing vessel.

4.1 Introduction

Formal Safety Assessment (FSA) is a new approach to marine safety which involves using the techniques of risk and cost-benefit assessment to assist in the decision making process. Upon carrying out the initial research on FSA, the history of its development and application was learnt and is explained here.

4.1.1 Cullen report

An explosion and subsequent fire on the Piper Alpha offshore installation led to the loss of 167 lives on the 6th of July 1988 [Department of Energy, 1990]. As a result of this, a public inquiry was established to discover the circumstances of the accident and its causes. The produced report (Cullen report) suggests that a safety case approach is required for the design of offshore installations.

A safety case covers all aspects of the safety of the plant or process in question, and determines how the risks involved are to be minimised. It should include sufficient data to demonstrate that:

- Hazards with the potential to cause major accidents have been identified.

- Risks have been evaluated and measures have been taken to reduce them to a As Low As Reasonably Possible level (ALARP) [HSE, 1992].

A safety case should be prepared demonstrating safety by design, describing operational requirements, providing for continuing safety assurance by means of regular review, and setting out the arrangements for emergency response. It should also include identification of a representative sample of major accident scenarios and assessments of the consequences of each scenario together with an assessment in general terms of the likelihood of it happening. The report suggests that innovative safety analysis methods and cost-benefit analysis may be beneficially used for the prediction and control of safety.

The reports recommends Quantitative Risk Analysis (QRA) to be used in the process of hazard identification and risk assessment in preparing a safety case. QRA can help to provide a structured objective approach to the assessment of risks, provided that it relies on and is supplemented by good engineering judgement and the limitation of the data used is roughly understood. The significant pathway leading to serious failure conditions can be systematically identified using QRA and hence all reasonably practicable steps can be taken to reduce them.

4.1.2 Development of FSA

Following the Cullen report and the recommendation of a safety case approach by the House of Lords Select Committee [House of Lords, 1992], it implied that the safety case approach should be considered in the long term for application to every ship trading commercially. The report envisaged that safety cases would require operators to demonstrate achievement of primary safety goals, including structural standards, operational competence and safety management for every type of ship operation. However, the impracticability of this in the international context of the shipping industry was recognised. In response to the Select Committees' report, the UK government published a report in December 1992, which reflected the above concern regarding the transferability of the safety case concept from the offshore industry to the shipping industry. Taking into account the increase in public concern regarding safety at sea and pollution prevention, the UK realised that the time was right for exploration of the safety case principles to be applied for shipping. Recognising the need for a change in the shipping regulatory framework, and in response to Lord Carvers' Report[1], the UK Maritime and Coastguard Agency (MCA) quickly responded and in 1993, proposed to the International Maritime Organisation (IMO) FSA be applied to ships. This is to ensure a strategic oversight of safety and pollution prevention. The UK MCA also proposed that the IMO should explore the concept of FSA, and introduce it in relation to ship design and operation. This proposal was submitted to the 62nd session of the Maritime Safety Committee (MSC) held from 24-28 May 1993 [Marine Safety Agency, 1993]. Since the approval of this proposal, the work for preparation of the FSA methodology and the guidelines for the application of FSA to the IMO rule making process have been mainly conducted by the inter-session correspondence group under the leadership of the United Kingdom.

Over the years, several applications of FSA have been attempted by the IMO on various vessels and systems. These include the application to the transportation of dangerous goods on passenger/ro-ro cargo vessels [IMO, 1998a], the effects of introducing Helicopter Landing Areas (HLA) on cruise ships [IMO 1998b], high speed catamaran passenger vessels [MSC, 1997a; MSC 1997b], novel emergency propulsion and steering devices for oil tankers [IMO, 1998d] and the trial application is on a bulk carrier [IMO 1998c, MSC, 1998b].

4.2 FSA

FSA is a new approach to the regulation of shipping safety. It has as its objective the development of a framework of safety requirements for shipping in which risks are addressed in a comprehensive and cost effective manner. The adoption of FSA for shipping represents a fundamental cultural change, from a largely reactive approach, to one, which is integrated, proactive and soundly based upon the evaluation of risk.

An FSA framework consists of the following steps:

[1] The report for the investigation carried out into the capsize of the Herald of Free Enterprise, which was published in 1992.

1) The identification of hazards (Step 1 Hazards).
2) The assessments of risk associated with those hazards (Step 2 Risks).
3) Ways of managing the risks associated with the hazards identified (Step 3 Control options).
4) Cost Benefit Assessment (CBA) of the options (Step 4 CBA).
5) Decisions on which options to select (Step 5 Decisions).

The interaction between the five steps can be illustrated in a process flowchart as shown in figure 4.1. As it can be seen, there are repeated iteration between the steps, which makes it effective as it constantly checks itself for changes within the analysis. The framework was initially studied at the IMO MSC in May 1993. Since then, several MSC meetings have been subsequently held to deal with FSA in more detail.

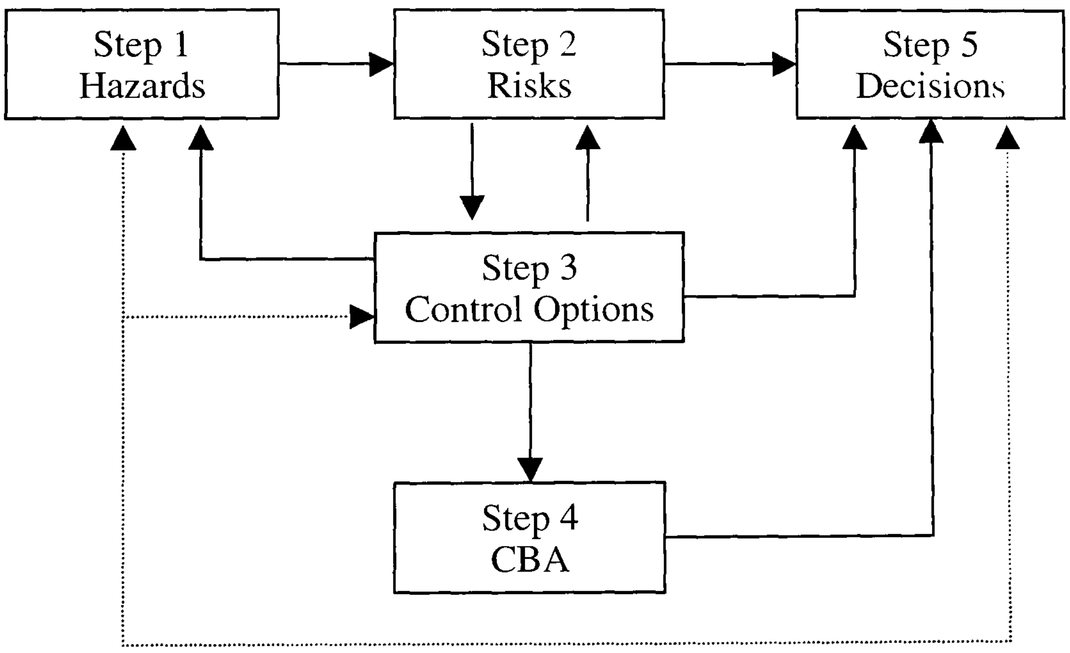

Figure 4.1. Flowchart of FSA process

Each step within the FSA can be further broken down into individual tasks and is represented in figure 4.2. The execution and documentation of each task is vital, as it will enable the preceding tasks/steps to be carried out with ease. In order for the assessment to be accurate, the analyst must understand and appreciate the objectives of each step and execute them without any "short-cuts".

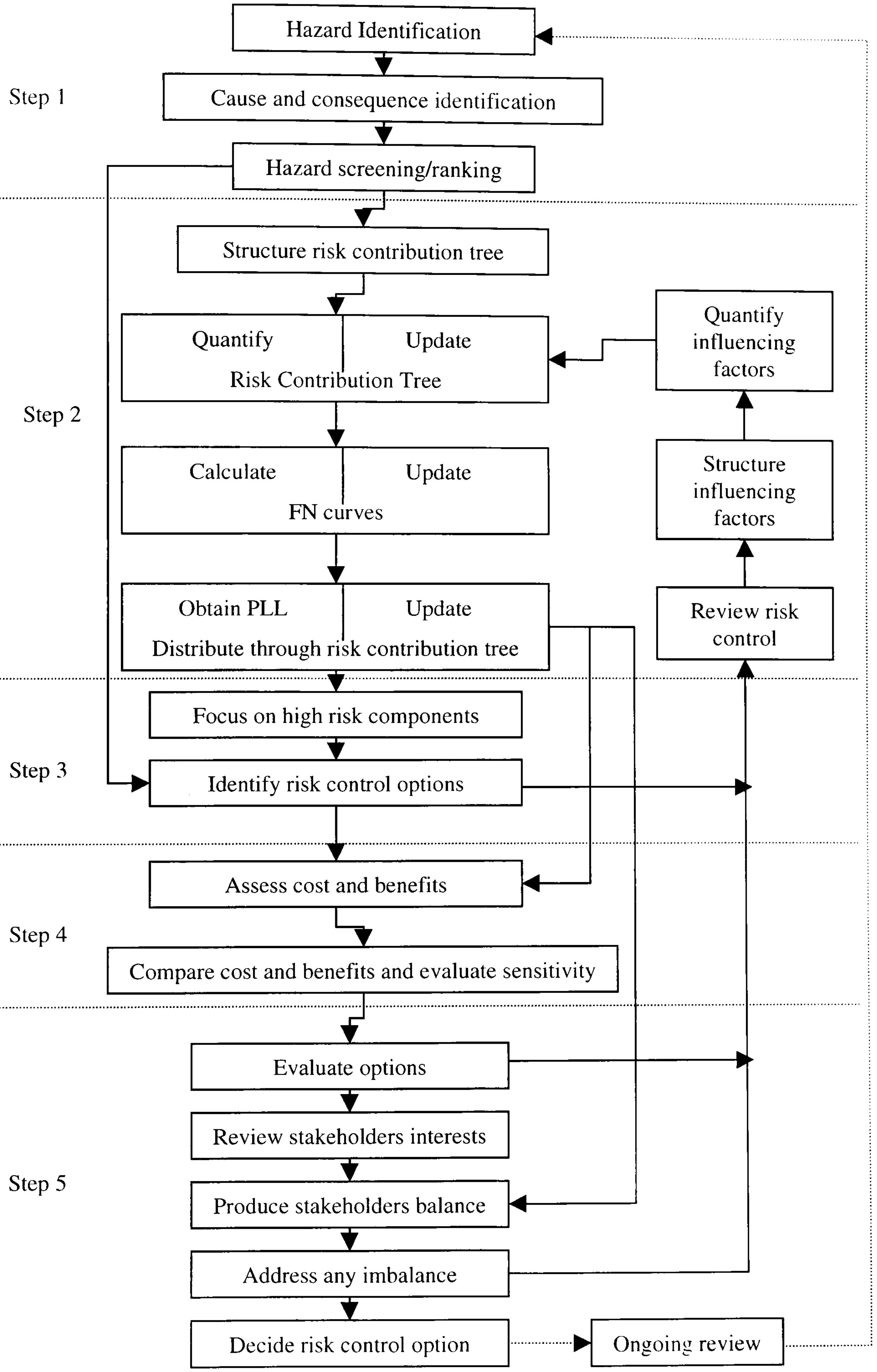

Figure 4.2 Detailed breakdown of FSA process

Depending on the requirement of the safety analysts and the safety data available. either a qualitative or a quantitative safety analysis can be carried out to study the risks of a system in terms of the probability of occurrence of each hazard and possible consequences. Qualitative safety analysis is used to locate possible hazards and to identify proper precautions (design changes, administrative policies, maintenance strategies, operational procedures, etc.) that will reduce the frequencies or consequences of such hazards.

4.2.1 Step 1-Hazard identification

Various safety analysis methods may be used individually or in a combination to carry out Step 1 of the FSA approach. Such typical methods include: Preliminary Hazard Analysis (PHA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Cause-Consequence Analysis (CCA), Failure Mode, Effects and Criticality Analysis (FMECA), HAZard and OPerability analysis (HAZOP), Boolean Representation Method (BRM) and Simulation analysis [Henley E.J. and Kumamoto H., 1996; Smith D.J., 1992; Villemeur A., 1992]. The use of these methods as safety analysis techniques has been reviewed in chapter 3.

In the hazard identification phase, the combined experience and insight of engineers is required to systematically identify all potential failure events at each required indenture level with a view to assessing their influences on system safety and performance. This is achieved using "brainstorming" techniques. The hazard identification phase can be further broken down into several steps as seen here.

Problem definition - Define the bounds of study, generic vessel and generic stakeholder for the vessel.

Problem identification - The problem boundaries of a FSA study can be developed in the following manner: range of vessel types, geographic boundaries, risks to be considered, vessel systems, relevant regulations and measures of risk. In addition, the following factors, specifically related to the vessel is defined: the generic vessel, vessel accident category, vessel stakeholders and vessel operational stages.

Hazard identification - The HAZard IDentification (HAZID) consists of determining which hazards affect the vessels' activities under consideration using "brainstorming" techniques. At the HAZID session the following information is gathered: operational stage, vessel system, hazards, causes and consequences.

Structuring HAZID output - The approach to structuring the HAZID output is to convert the information gathered at the HAZID meeting into hazard worksheets which records the causes, accident sub-categories, consequences and the source of information. These hazard worksheets provide a means for recording the output from the HAZID meeting and other hazards identified during the analysis period, e.g. from incident database or interviews with the vessel personnel.

Risk exposure groups - The next step is to group the causes into risk exposure groups. This is achieved by using the guidewords taken from the risk exposure source given in MSC 68/14 [IMO MSC, 1993]. The groups are then further sub-divided, during the hazard-structuring phase into risk exposure sub-groups. An example of this can be found in [MSC, 1997b]. In order to sort the large amount of information collected at the HAZID meeting, accident sub-categories are established for each accident category and all the identified consequences are grouped according to contributing factors.

Hazard screening - The purpose of hazard screening during Step 1 is to provide a quick and simple way of ranking hazards. It is a process for establishing, in broad terms, the risks of all identified accident categories and accident sub-categories, prior to the more detailed methods of quantification, which will be used in Step 2. Risk is a combination of the frequency of occurrence of an accident type with the severity of its consequences. The generic unit of the consequence is loss, which may be loss of lives, environmental pollution or damage to ship/cargo or financial loss. Accordingly, risk can also be read as the estimated loss in a given period of time. Two approaches can be used for the assignment of screening risk level in order to check the robustness of the resulting hazard rankings and to assist in the resolution of the rankings in cases where several hazards have similar ranking levels. These approaches are:

- Risk matrix approach [Loughran C.G. et. al., 1999].
- Cumulative loss approach [MSC, 1997a].

4.2.2 Step 2-Risk estimation

Information produced from the hazard identification phase will be processed to estimate risk. In the risk estimation phase, the likelihood and possible consequences of each System Failure Event (SFE) will be estimated either on a qualitative basis or a quantitative basis (if the events are readily quantified). The risk estimation phase can be further broken down into several steps as seen here.

Structuring of Risk Contribution Tree (RCT) - The causes and outcomes that were identified in Step 1 are structured in Step 2 for its employment in various parts of the Risk Contribution Tree (RCT). The RCT is structured in two distinct ways. Below the accident category, the structure is a graphical representation of the accident sub-categories and of the combinations of contributory factors relevant to each accident sub-category. Its structure is similar to a Fault Tree in its use of logical symbols, and the term "Contribution Fault Tree" has therefore been employed. Above the accident category level, the structure is an event tree representation of the development of each category of accident into its final outcome. An example of a RCT is provided in Appendix 4.

Structuring and quantification of influence diagrams - The purpose of influence diagrams is to identify the influences, which effect the likelihood of an accident, and to enable those influences to be quantified. It also provides information for use in Step 3 of the FSA process. An example of an influence diagram for a fire accident in given in Appendix 5. An influence diagram takes into account three different types of influence, which are due to:

- Human failure
- Hardware failure
- External event

Additionally, each influence diagram incorporates dimensions of design, operation and recovery[2].

Quantification of RCT - The quantification of the RCT is accomplished by using available historical data from the incident database and where such data is absent, expert judgement is used to complement the quantification. The level of potential consequences of a SFE may be quantified in economic terms with regard to loss of lives/cargo/property and the degradation of the environment caused by the occurrence of the SFE. Finally, the calculation of FN curves and Potential Loss of Life (PLL) through the RCT is carried out. Both FN curves and PLL measures the risks that have been derived.

4.2.3 Step 3 - Risk Control Option (RCO)

The next step aims to propose effective and practical Risk Control Options (RCOs). Focusing on areas of the risk profile needing control, several RCOs are developed and recorded in a Risk Control Measure Log (RCML). Upon identifying all possible RCOs for the identified risks, the RCOs in the RCML is used to generate a Risk Control Option Log (RCOL). The information in the RCOL will be used in Step 4 of the FSA process.

In general, RCO measures have a range of following attributes:

- Those relating to the fundamental type of risk reduction (preventative or mitigating).
- Those relating to the type of action required and therefore to the costs of the action (engineering or procedural).
- Those relating to the confidence that can be placed in the measure (active or passive, single or redundant).

The main objective of the RCO is to reduce frequency of failures and/or mitigate their possible consequences.

[2] Recovery refers to taking remedial action to recover from an error or failure before the accident occurs.

4.2.4 Step 4 - Cost-Benefit Analysis (CBA)

Upon gathering the various control options, the next step is to carry out a Cost-Benefit Analysis (CBA) on each option. CBA aims at identifying the benefits from reduced risks and cost associated with the implementation of each risk control option for comparison. The evaluation of costs and benefits may be conducted using various techniques [IMO MSC, 1993]. It should be initially carried out for the overall situation and then for those interested entities influenced by the problem consideration.

4.2.5 Step 5 - Decision-making

The final step is the decision-making phase, which aims at making decisions and giving recommendations for safety improvement. At this point, the various stakeholders' interest in the vessel under study is considered. The cost and benefit applicable to each stakeholder has to be determined in order to decide the best risk control option – each RCO will have a different impact on the identified stakeholders, as such, the most effective RCO should strike a balance between the cost and benefit for each stakeholder. In reality, this is not always possible, hence, any imbalance has to be addressed and justified before the selected RCO is accepted as being the best option. The information generated in Step 4 of the FSA process can be used to assist in the choice of a cost-effective RCO. However, the cost factor may not be the only criterion that should be considered. As such, at this stage, certain multi criteria decision-making techniques should be employed to select the most favourable RCO [Wang J. et. al., 1996; Pillay A. and Wang J., 2001].

4.3 An FSA Framework for a Generic Fishing Vessel

The proposed FSA framework for a generic fishing vessel by the author, is based on the FSA methodology described in section 4.2 and can be developed into five steps for ease of understanding as follows:

1) Hazard identification.
2) Risk quantification.
3) Risk ranking.

CHAPTER 7 - MAINTENANCE MODELLING

CHAPTER 8 - HUMAN ERROR ASSESSMENT AND DECISION MAKING USING ANALYTICAL HIERARCHY PROCESSING

4) Recommendations.

5) Decision-making.

These five steps are represented in a flowchart as seen in figure 4.3. These steps are further complemented by the work completed in this project and presented in the various chapters of this thesis. The interaction of the proposed framework and the parts developed in this thesis can be seen in figure 4.4. This method is aimed at enhancing fishing vessel safety, including protection of life, health, the marine environment and property, by using a systematic risk based analysis. The proposed method can be viewed as a simplified version of the method discussed in section 4.2.

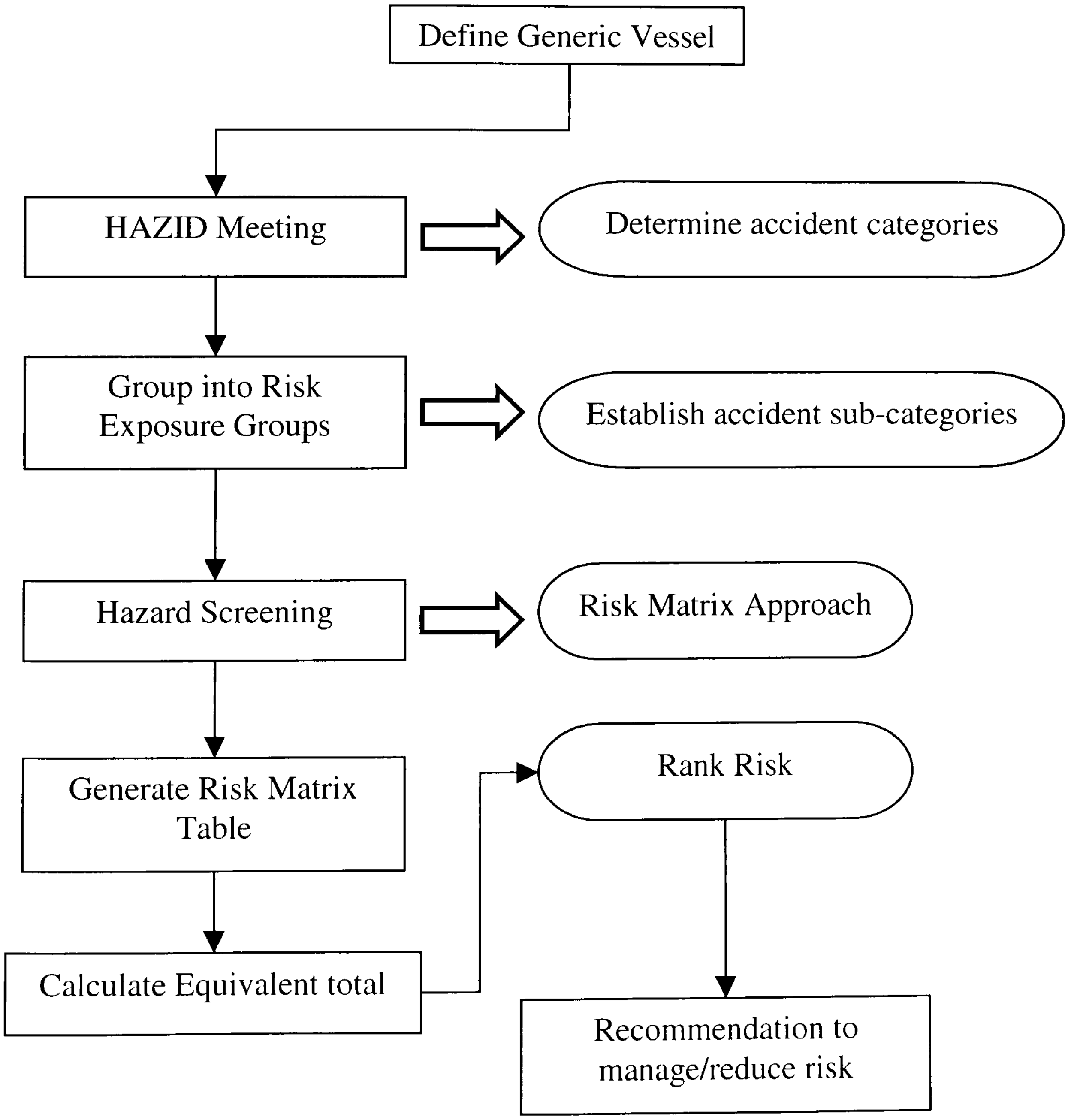

Figure 4.3 Flowchart of proposed approach

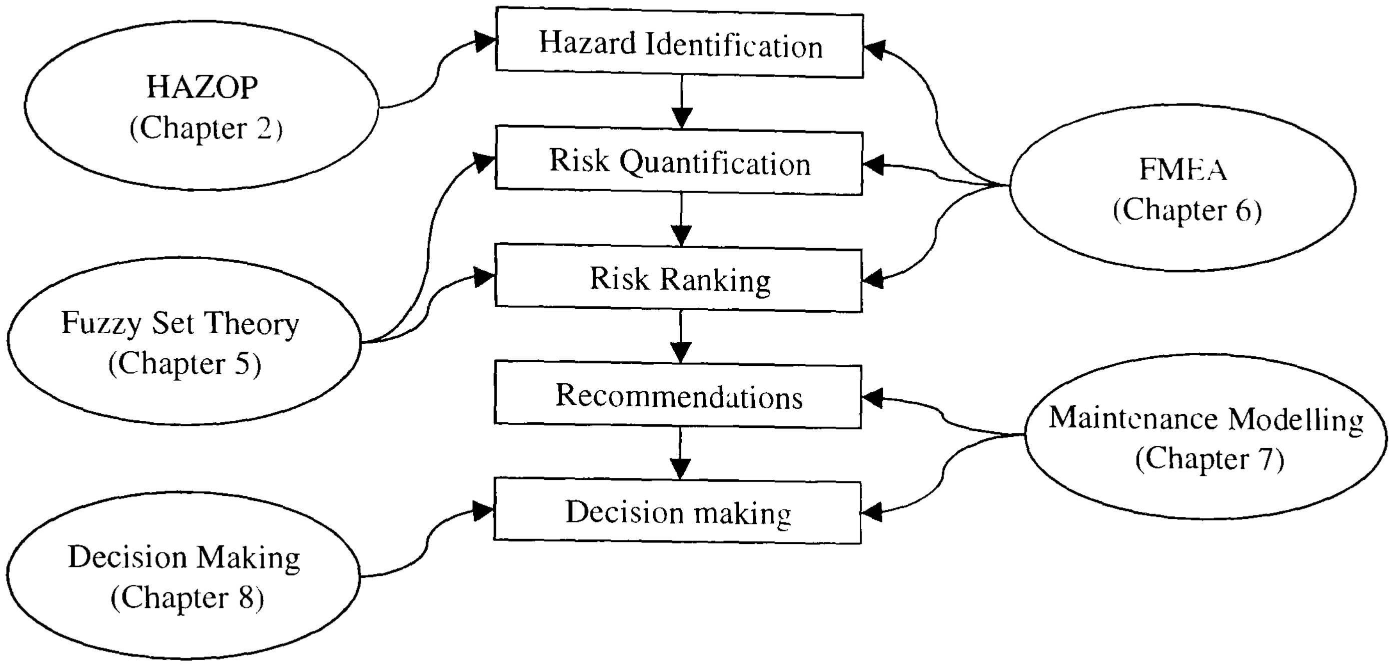

Figure 4.4 Methods developed for the FSA framework of a generic fishing vessel

4.3.1 Generic fishing vessel

A generic model fishing vessel should be defined in order to describe the function, features, characteristics and attributes, which are common to all ships of the type, or relevant to the problem under study [MSC, 1998a]. The generic vessel facilitates an understanding of the subject under study and can be used to help identify relevant accidents and accident sub-categories, leading to an enhancement of the HAZID structuring. The description of the generic fishing vessel can be divided into several aspects as seen in figure 4.5 and explained here:

Power/Propulsion - Auxiliary power of fishing vessels are normally provided by two or more diesel-electric generator sets or possibly main engine driven alternators on smaller vessels. Power distribution is by series switchboards, distribution panels and cabling systems. Emergency power sources are normally battery based. Medium speed engines (via a reduction gearing system) normally provide the propulsion power.

Bunkering - Bunkering operation is normally undertaken with manual connection of fuel from shore to a receptor on the vessel. Fuel used for fishing vessels has a flash point of no less that 43 degrees Celsius.

Communications - These are pre-dominantly external communication components, which consist of VHF, MF, HF and Satcom systems with EPIRBs (Emergency Position Indicating Radio Beacon) and SARTs (Search and Rescue Transponder) for emergencies. Larger deep-sea fishing vessels have internal communication components such as the public address system and telephone system to particular crew or operational area.

Control - This covers the control of the entire ship. The bridge or wheelhouse is generally the central and often the only control centre on fishing vessels. The bridge has facilities for all round vision, communication, navigation, safety and ship control equipment. The main machinery spaces are periodically manned (during manoeuvring) and unmanned during fishing operations. Local control positions are available for all fishing gear with some limited remote controls on the bridge.

Emergency response/control - The fishing vessel is expected to be equipped to react to emergencies such as rescue from water (either man overboard or third parties). Most vessels carry on board first-aid kits to administer first aid in case of an accident.

Habitable environment - The crew of the fishing vessel are provided with a habitable environment. This may require consideration of ship motion, noise, vibration, ventilation, temperature and humidity. Most accommodation areas of the vessel are provided with intake and exhaust blowers. Where there is an engine control room fitted, it is provided with an air conditioning system as with the navigation bridge.

Manoeuvring - Fishing vessels do not particularly need an accurate and sensitive manoeuvring system. However, when carrying out pair trawling (where two or more vessels are moving closely together), it could be vital to avoid collisions and contacts. Rudders are used with conventional propeller propulsion systems. There are no bow or stern thrusters fitted on fishing vessels.

Mooring - Mooring during berthing operations is normally undertaken in a conventional manner using rope mooring lines, fairleads, bollards and winches.

Anchoring - Anchoring arrangements are provided for all fishing vessels and comprise of light weight-high holding power anchors with wire or fibre ropes for the main anchor line.

Navigation - Fishing vessels are normally fitted with a magnetic compass, a speed and distance measurement device, a depth of water indicator, one or more radar and an electronic positioning system. Vessel fixing procedures using visually observed bearings are generally carried out on deep-sea fishing vessels and not on smaller coastal fishing vessels.

Payload - The payload of fishing vessels consists of both processed and pre-packed fish (vessels with fish factory on board) or loose fish stored in the cargo holds. The fishing gear on board the vessel is also considered to be part of the payload. Unloading is normally via shore cranes and forklifts - frozen fish packages are placed on pallets and then lifted by a shore crane from the ship to be placed on the docks. Once the fish pallets are on the dock, it is transferred either into a shore freezer holding area or directly onto a truck by the forklift.

Pollution prevention - Oily bilge water is stored on board and discharged to a shore receptacle when the vessel berths for unloading. Oily water separators are rarely provided for smaller coastal vessels. Engine exhaust gases are normally visually monitored.

Stability - The stability requirements of fishing vessels are normally assessed for a range of loading and operating conditions. They relate to intact and damage stability consideration including effects of wind, sea condition and loads on fishing gear during fishing operation.

Structure - The material used for the construction of a fishing vessel include wood, aluminium, fibre-reinforced plastics, high tensile steel and ferro - cement. The arrangements of aluminium and steel structures normally consist of shell plating supported by longitudinal members and, in turn by transverse frames. The structure must withstand the envisage forces imposed, which include sea forces, dead loads, cyclic forces, towing, docking and general robustness criteria.

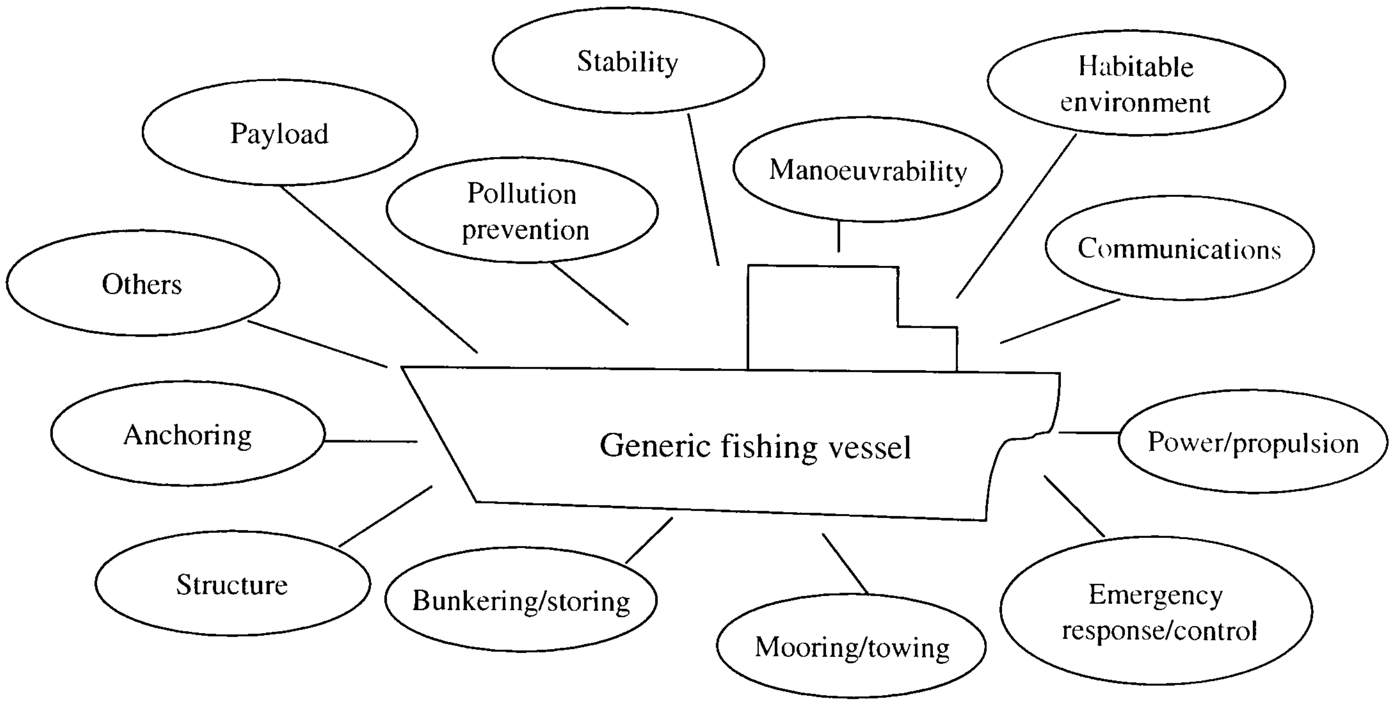

Figure 4.5 A generic fishing vessel

The generic fishing vessel is epitomised to be a hypothetical vessel of any size and method of fishing. To summarise, it is an appraisal of the functions of operation that is necessary for any fishing vessel. Fishing being a combined production and transport operation, is cyclic with the following distinct phases of life:

- Design, construction and commissioning.
- Entering port, berthing, un-berthing and leaving port.
- Fish loading
- Fish unloading.
- Passage.
- Dry dock and maintenance period.
- Decommissioning and scraping.

A generic fishing vessel may also be thought of as being a combination of hard and soft systems as listed below:

- Communications
- Control

- Electrical
- Human
- Lifting
- Machinery
- Management system
- Navigation
- Piping and pumping
- Safety

4.3.2 HAZID

The first step of the analysis is the hazard identification. This consists of determining which hazards affect the fishing vessels' activities under consideration using 'brainstorming' techniques involving trained and experienced personnel. In the HAZID phase, the combined experience and insight of engineers is required to systematically identify all potential failure events at each required indenture level with a view to assessing their influences on system safety and performance. Various safety analysis methods may be used individually or in a combination to identify the potential hazards of a system. These methods have been detailed in chapter 3.

In the HAZID meeting, accident categories are determined for the safety analysis. As a guide, the accident categories determined by the Marine Accident Investigation Branch can be used [Loughran C.G. et. al., 2001]. These categories can be seen in chapter 2 (section 2.5) and are summarised here:

- Foundering and flooding
- Stranding and grounding
- Collisions and contact
- Capsizing and listing
- Fires and explosions
- Machinery damage
- Heavy weather damage
- Missing vessels
- Loss of hull integrity
- Others

Having identified the accident categories, the causes are then grouped into the following risk exposure groups:

1. Human Errors

Human Performance -Communication

	-Navigation -Competency -Fishing -Anchoring -Mooring -Abandonment
Commercial Pressures	-Manning -Finance -Company or firm procedures
Management Systems	-Onboard management -Loading fish -Shore side systems

2. Hardware failures

-Material of construction
-Structure
-Propulsion
-Steering
-Piping and plumbing
-Control
-Electrical
-Refrigeration
-Safety systems
-Habitable environment
-Emissions control
-Bunkering and storage
-Diagnostics systems
-Maintenance systems

3. External Events

Environment	-Pollution prevention -Climatic variations
Payload	-Fish handling, loading and storage -Crane/lifting mechanisms -Berthing

In order to sort the large amount of information collected at the HAZID meeting, a set of accident sub-categories is established as follows:

Collision and contact accident sub-category

- Berthed
- Starting up
- Loading and unloading in port
- Departing and manoeuvring close to the berth
- Manoeuvring in harbour and close to harbour
- Passage in open sea
- Loading fish at sea
- Entering harbour
- Arrival manoeuvring close to the berth
- Shutdown
- Abnormal operation
- Maintenance
- Anchored
- Dry-docked

Fire accident sub-category

- Engine room
- Fish room space
- Wheelhouse
- Accommodation
- Galley

Loss of hull integrity accident sub-category

- Hull Plating
- Framing
- Bulkheads
- Welds and joints
- Penetrations
- Seals
- Appendages
- Opening or failure of doors
- Opening or failure of scuttles
- Other

4.3.3 Hazard screening

The risk matrix approach is used in the hazard screening process. For each appropriate combination, an assessment is made of the frequency (F) of the accident, and the severity (S) of the consequences in terms of human injuries/deaths, property damage/loss and the degradation of the environment. The corresponding Risk Ranking Number (RRN) is then selected from the risk matrix table. This method allows for expert judgements where detailed data is unavailable. Ranking of the various accidents determines their order in relation to one another. In short, the RRN is indicative of the relative order of magnitude of risk.

Table 4.1 shows the risk matrix table that presents in a tabular format, a risk level related to the frequency and severity of an accident. RRN ranges from 1 (least frequent and least severe consequence) to 10 (most frequent and most severe consequence).

		F1	F2	F3	F4	F5	F6	F7
S1	**Minor Injuries**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
S2	**Major injuries**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
S3	**1 to 10 Deaths**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
S4	**> 10 Deaths**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Table 4.1 Risk matrix table

Table 4.2 gives the interpretation of the frequencies F1 to F7 as determined by [MSC, 1998a], in terms of a generic fishing vessel based on the following estimations:

1. Vessel life expectancy – 25 years
2. Operational days per year – 250
3. Operational hours per day – 13
4. Major maintenance per year – 1

Likely to happen On a vessel once per Frequency	**General Interpretation**	**Generic fishing vessel Interpretation**
F1 10000 – 100000 years	Extremely remote to extremely improbable	Likely to happen every 20 yrs in the industry
F2 1000 – 10000 years	Remote to extremely remote	Likely to happen every 2 yrs in the industry
F3 100- 1000 years	Remote	Likely to happen 5 times per yr in the industry
F4 10 – 100 years	Reasonably probable to remote	Likely up to 3 times per vessel life
F5 1 – 10 years	Reasonably probable	Likely up to 15 times per vessel life
F6 Yearly	Reasonably probable to frequent	Likely annually per vessel
F7 Monthly	Frequent	Likely monthly per vessel

Table 4.2 Key to risk matrix table

Using the risk matrix approach, for each accident category, a ranked risk table is produced, listing all accident sub-categories against each generic location. An example of this is seen in table 4.3, where F is the frequency and S is the severity of the accident. The number in the brackets, (x), is the corresponding RRN obtained from table 4.1. Upon completing the risk table, the next task is to determine the "Equivalent Total" for each accident category.