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FORMAL FIRE SAFETY ASSESSMENT OF PASSENGER SHIPS

By

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ABSTRACT

Fire has been a major cause of ship's accidents throughout maritime history. It is by far the most serious threat to life and the environment as passenger ships get larger and more sophisticated. It is also impossible to protect a passenger vessel against all hazards. Despite the fact that a passenger ship contains potential fire hazards in the engine room space, accommodation zone and electrical systems, etc, the single most important fire hazard onboard a ship may be the man himself, either unintentionally or intentionally. 'Fire safety on passenger vessel' has continued to be the focus of attention on passenger ships.

The work described in this thesis is concerned with the application of Formal Fire Safety Assessment to passenger ships. The traditional way of conducting a Formal Safety Assessment (FSA) employs typical fire safety analysis methods that require a certain amount of data. Most fire accident data available for passenger vessels is associated with a high degree of uncertainty and considered to be unreliable. As such, the research carried out in this thesis is directed at the development of novel fire safety analysis methods to address this problem.

This thesis proposed several subjective fire safety analysis methods for passenger vessels within the FSA methodology. Also, it concentrates on developing an advanced approach for passenger ships.

A few novel safety analysis and synthesis methodologies are presented to integrate fire safety assessment with decision-making techniques so that fire safety can be taken into account from the concept design /operation stages of passenger ships. This is to ensure a more controlled development process permitting decisions regarding design and operation to be made based on fire safety assessment.

Finally, this thesis is concluded by summarising the results of this research project and the areas where further effort is required to improve the developed methodologies.

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ABBREVIATIONS

AHP	Analytical Hierarchy Processing
ALARP	As Low As Reasonably Practicable
ASCS	Active Smoke Control System
BSI	British Standards Institute
CA	Criticality Analysis
CCA	Cause-Consequence Analysis
CURR	Cost per Unit Risk Reduction
EE	Electrical Equipments
ET	Event Tree
ETA	Event Tree Analysis
EVI	EVacuability Index
FAST	Fire-growth And Smoke Transport
FN	Frequency-Number
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FO	Fuel Oil
FP	Fire Prevention
FRI	Full Room Involvement
FSA	Formal Safety Assessment
FSEG	Fire Safety Engineering Group
FT	Fault Tree
FTA	Fault Tree Analysis
G/E	Generator Engine
HRR	Heat Release Rate
HVAC	Heating, Ventilation and Air Conditioning
IACS	International Association of Classification Societies
ICAF	Implied Costs of Averting a Fatality
IDS	Intelligent Decision System
IMO	International Maritime Organization
ISM	International Safety Management

ISO	International Organization for Standardization
LLL	Low Location Lighting
LO	Leakage Oil
LR	Lloyd's Register
MADM	Multiple Attribute Decision-Making
MCA	Maritime Coastguard Agency
MCDM	Multiple Criteria Decision-Making
M/E	Main Engine
MVZ	Main Vertical Zone
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NK	Nippon Kaiji
PLL	Potential Loss of Lives
PRA	Probabilistic Risk Assessment
QRA	Quantitative Risk Analysis
RCM	Risk Control Measure
RCO	Risk Control Option
RRN	Risk Ranking Number
RTI	Response Time Index
RTS	Run Time Simulator
SFSE	Society of Fire Protection Engineers
SOLAS	Safety Of Life At Sea
SSRC	Ship Stability Research Centre
T/C	Turbo Charger
WO	Waste Oil

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CHAPTER 1 - INTRODUCTION

Summary

This chapter describes the concepts of fire safety assessment and reliability analysis with some problems encountered in applying the existing reliability and safety analysis methods in quantitative safety appraisal studies, especially in the early concept design stage. This chapter also outlines a philosophy aimed at facilitating the development of a formalised environment for safer ships by adopting an integrated approach, involving the incorporation of fire safety assessment with technological design and development in an iterative manner. Finally, the objectives of this work are described and the scope of this thesis is outlined.

1.1 Background in Fire Safety

Statistics indicate that a ship is lost to fire every ten days [LR, 1988]. The history, philosophy and development of marine fire protection are best traced by focusing on passenger ship. Passenger vessels have the largest potential for loss of life and are the subject of long–standing international attention and regulatory effort [Ohnstad, 1991]. Therefore, the following overview primarily regards such passenger vessels and should aid readers in understanding the philosophy that was employed in developing the current international requirements.

The tragic sinking of the *Titanic* on the 14th April, 1912 focused international concern on the Safety Of Life At Sea (SOLAS), and in 1914 the first international conference was held to discuss shipboard safety [Ohnstad, 1991]. This conference focused on subdivision and lifesaving. Concerns regarding fire safety were not addressed until 1929 when a second conference was held. This conference produced the Convention for SOLAS that was later ratified in 1936.

A tragic fire aboard the US flag passenger vessel *Morro Castle* in 1934 claimed the lives of 124 persons and fuelled public sentiment to improve vessel fire safety. The

US Senate Committee on Commerce formed a special subcommittee on fireproofing and fire prevention to develop recommendations for fire safety standards on ships. The subcommittee noted the vulnerability of complex automatic and manually controlled fire detection, extinction systems and agreed that the most fool-proof approach would be construction of such nature that it would confine any fire to the space in which it originated. This remains a key principle in the current international regulations. The latest Convention, SOLAS 1974, came into effect internationally in May, 1980. It has been amended several times since then.

As far as the marine industry is concerned, tragic accidents have focused world opinion on ship safety and operation. This demand for improved fire safety requires comprehensive fire safety analyses to be developed in order to identify ways to control risks. Such fire safety analysis models will ensure efficient, economic and safe ship design and operation.

1.2 Background to Fire Safety Assessment

It is becoming necessary to develop and apply more rational techniques which permit quantification of safety, reliability and risk of failure [Aldwinckle & Pomeroy, 1982]. By using a rational approach based on reliability techniques and the novel techniques as proposed in this thesis, fire safety assessments can be conducted for any project at the concept design stage, the later design stage and operational stage. The author does not wish to suggest that these novel techniques should replace the well-proven methods used in maritime and other industries for safety assurance but they might be used as an enhancement where circumstances dictate, in particular at the early concept design stage. These novel techniques can assist designers and operators in analysing the effects of failure on safety and operability, especially for systems with a high level of innovation.

Some commercial institutions have focused on developing databases of maritime accidents [Hill, et al., 1994] [OREDA, 2002] [P & I Club, 2003]. Unfortunately, accident statistics were not gathered systematically in the past and there is a lack of data. Furthermore, the available information is often not gathered consistently and as a result its users cannot often be sure whether a set of data is really applicable to the situation in question.

The reliability and safety assessment methods are well established and universally applicable being a combination of logic and statistics. It is anticipated that ships, and especially those passenger vessels will become more dependent on complex systems of integrated components and such methods of analysis will not only be more relevant but also become a necessary part of both design and operation. Owing to the growing level of innovation of the modern engineering products such as passenger ships, novel methods are required to deal with the reliability and fire safety aspects, in particular, at the early concept design stage.

Fire safety analysis is a very complicated subject where safety is determined by numerous factors including fire. Many fire safety assessment techniques currently used in maritime industries are comparatively mature tools. However, in many circumstances, the application of these tools may not be suitable or give satisfactory results due to the lack of safety related data or the high level of uncertainty involved in the safety data available. Novel fire safety analysis methods are therefore required to identify major hazards and assess the associated risks in an acceptable way in various environments where mature tools cannot be effectively or efficiently applied. The literature search carried out by the investigator indicates that although some work has been conducted in this area, very limited formal safety based decision support tools have been developed and applied to a stable environment in the maritime industry. Fire safety based decision support techniques may help the designers in determining where risk reduction actions are required, defining appropriate risk reduction measures and reducing cost without increased risks to the maritime system.

Some novel fire safety assessment methods and safety-based decision support tools will be developed to facilitate fire safety analysis in such situations.

1.3 Aim and Objectives

The main aim of this project is to develop an environment that adopts an integrated approach to the management and control of the passenger vessel design and fire safety issues involved and their interaction.

The main objectives of this research are:

1. To identify fire safety assessment techniques currently used in the passenger ships, which include methods for hazard identification, risk quantification and decision-making.

2. To study the Formal Safety Assessment (FSA) approach in maritime safety applications.

3. To develop novel fire safety assessment techniques and decision support approaches to facilitate maritime safety analysis of passenger vessels.

4. To identify the best way whereby safety on board passenger ships can be assured and to develop a suitable model to assist in its implementation.

5. To identify further research areas required to be exploited in the future.

1.4 Scope of the Work

The fire safety analysis and decision support methodologies developed and described in this work are of general nature, therefore they are theoretically applicable to the design and safety related assessment of a wide range of complex engineering products such as passenger vessels. They are also appropriate for other disciplines of engineering work, especially in situations when the relevant safety-related information is lacking. The developed methodologies can be used together with the conventional methods in fire safety assessment, in particular for engineering products with a high level of innovation. The body of the thesis is structured in ten chapters. A brief outline of the content of each chapter is given below.

Chapter 2 outlines a comprehensive statistical data analysis of the vessels. The data that was collected and analysed from various sources, are presented in the form of graphs and tables to enable easy reading. The findings of the accident data gathered and the problems of lack or incomplete data to carry out passenger vessel fire safety assessment are discussed.

Chapter 3 discusses the inception of FSA. 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 risk control options; making decisions on which options to select. These five steps are briefly discussed, highlighting the interaction and continuity of each step. Reiteration within the FSA process is expressed by means of a flowchart. A general framework for the application of the FSA to generic passenger vessel is proposed and is demonstrated using a test case. The typical risk and fire safety assessment techniques are also described. The advantages and disadvantages of each method are reviewed.

Chapter 4 proposes an approach for fire modelling of accommodation zone of passenger ships. The example performed summarises the basic assumptions, the models and the calculation procedures employed to analyse a possible fire scenario in an accommodation zone of a passenger ship.

One of the most important means to avoid catastrophes in case of fire onboard passenger ships is to ensure that the passengers can escape in a quick and safe manner. One of several precautions to take is to try to control the spread of the smoke in a simple and reliable way. In this way the area where people are in contact with the smoke can be minimised and better visibility to escape from the smoke can be secured. *Chapter 5* develops in smoke control philosophy for accommodation area.

Chapter 6 describes a new approach for evacuation analysis using computer simulation. This chapter includes the simulation of 90 passengers and 10 crew members mustering on a vessel with 6 decks. After this, simulation of different scenarios is discussed.

Chapter 7 presents a risk modelling approach which incorporates the use of approximate reasoning method in engine room applications. This chapter concentrates on the fire risk evaluation of the major hazards threatening the engine room overall rather than focusing on specific areas of the design. A case study of the risk to passenger ship engine room due to fire during operation is used to illustrate the application of the proposed risk assessment model.

Chapter 8 examines a new design-decision support framework for evaluation of machinery space. In this chapter, a design-decision support framework using a composite structure methodology grounded in approximate reasoning approach and evidential reasoning method is suggested for design evaluation of machinery space of a ship engine room at the initial stages.

Chapter 9 proposes a framework for the identification and quantification of fire in passenger vessel operation. The method uses Analytical Hierarchy Processing (AHP) theory to rank the preference of each risk control option. The advantages of employing the AHP technique are discussed.

Finally conclusions and recommendations are provided in *Chapter 10*.

The logical sequence and interrelations among the chapters of the thesis are illustrated in Figure 1.1.

1.5 Contributions and Dissemination

This thesis proposed several subjective fire safety analysis methods for passenger vessels within the FSA methodology. Also, it concentrates on developing an advanced approach for passenger ships.

A few novel safety analysis and synthesis methodologies are presented to integrate fire safety assessment with decision-making techniques so that fire safety can be taken into account from the concept design /operation stages of passenger ships. This is to ensure a more controlled development process permitting decisions regarding design and operation to be made based on fire safety assessment.

In general, the results of the project can be tailored for fire safety analysis of any maritime engineering product with domain-specific knowledge and therefore can be used in many engineering applications.

Investigation results and findings are made available by publications in journals and presentation at international conferences. Some publications arising from this investigation are listed in Appendix 1 at the end of this thesis.

References

Aldwinckle, D. S. & Pomeroy, R. V. (1983), "Reliability and Safety Assessment Methods for Ships and Other Installations", Lloyd's Register of Shipping Technical Paper, London, UK.

Hill, S. G., Byres, J. C., Rothblum, A. M. & Booth, R. L. (1994), "Gathering and Recording Human Related Casual Data in Marine and Other Accident Investigation", Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting, Nashville, USA, pp 863-867.

LR (1988), "1986 and 1987 Casualty Records", Lloyd's Register of Shipping, London, UK.

Ohnstad, S. J. (1991), "Fire Protection in Merchant Ships – An Overview", The Management of Safety in Shipping, The Nautical Institute, London, UK.

OREDA (2002), "Offshore REliability DAta handbook (OREDA)", PennWell Books.

P & I Club (2003), "Protection & Indemnity Review 2003", MARSH Ltd.

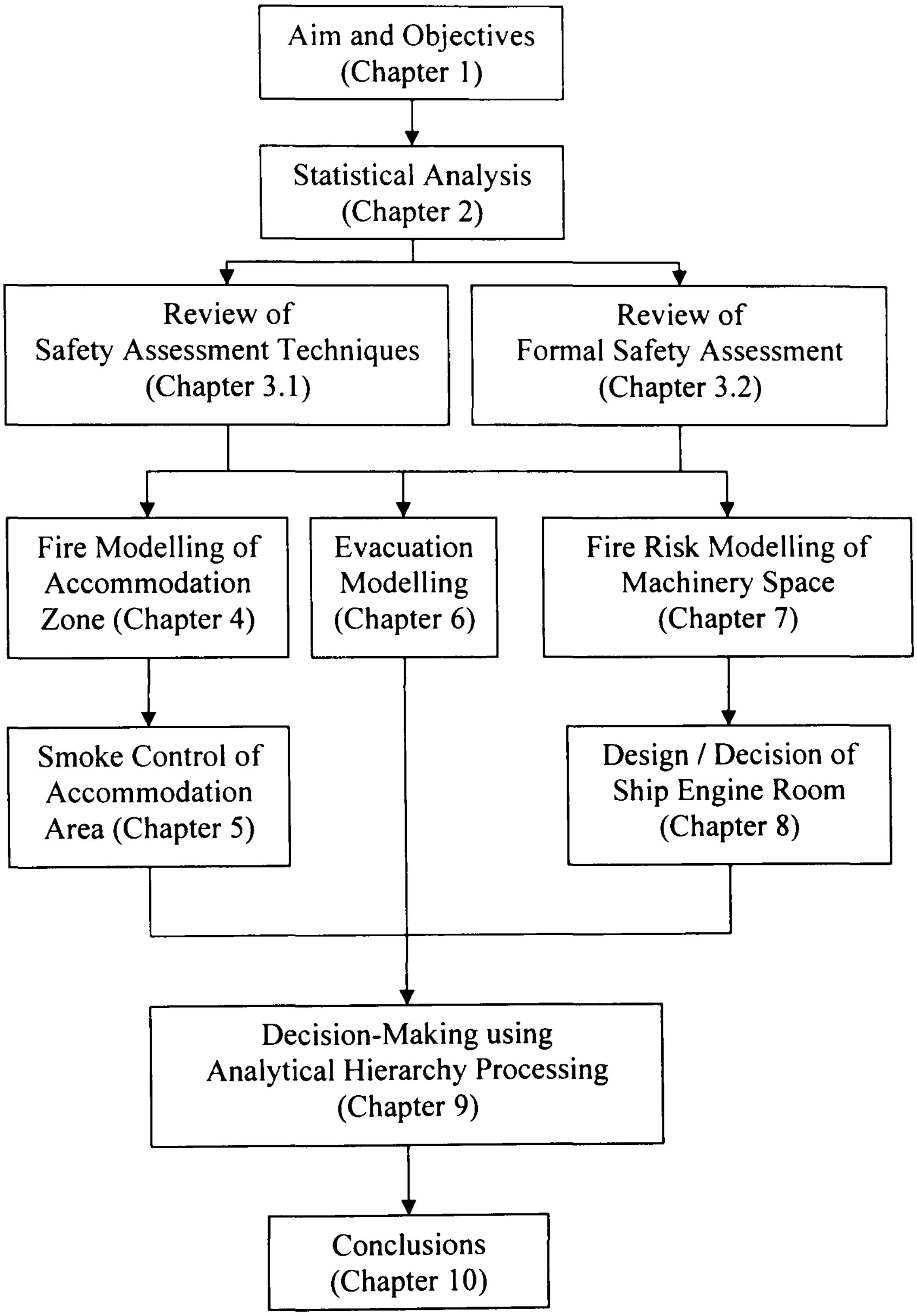


Figure 1.1. Structure of the thesis.

CHAPTER 2 – A STATISTICAL STUDY OF PASSENGER VESSELS

Summary

This chapter briefly reviews the current rules and regulations governing passenger ships and presents the fire safety programmes implemented by the governing bodies. This chapter demonstrates that there is a need for improvement in fire safety performance.

2.1 Introduction

The most recent biggest passenger vessels have been designed to carry more than 3,000 passengers, 1,500 crew and other staff members. The needs of the market will probably lead in the near future to the building and operation of passenger ships with more and more passengers on board, suited to different types of clients (couples, families and groups), with large public spaces (restaurants, cinemas, discos, casinos and sports and other forms of entertainment) and very high comfort on board. The setting inside the ship is to be at least as beautiful and impressive as the setting outside.

Due to world cruise demand, which foresees doubling the number of passengers by the year 2010, the building of large passenger ships is expected to growing carry on.

The International Maritime Organisation (IMO) Secretary General [IMO, 1999], while recognising the achievements of the shipbuilding and ancillary industries in delivering gigantic passenger ships embodying state-of-the-art technology, expressed the wish that the IMO undertake a global consideration of safety issues pertaining to passenger ships, with particular emphasis on large cruise ships.

Several questions may arise:

1. What are the necessary solutions to deal with safety of these vessels?

2. Can present rules and regulations, concerning the safety of the ship, passengers and crew but derived from ships of smaller dimensions, cope with such an explosion of needs and creativeness?

3. Safety records of incidents and accidents of passenger ships are good, especially for the latest generation of ships, but are the present solutions adequate to cope with the above mentioned growth and the needs of this industry?

The present large passenger ships are built in accordance with international regulations derived from experience in the past for ships of smaller dimensions. However, a lot of improvements have already been foreseen by the designers, often going beyond the sole strict application of present rules and regulations, taking into account the number of passengers and crew on board [Cazzulo & Fanciulli, 2000]. The most interesting features presently foreseen or under discussion for future new buildings are about fire safety and means of escape and evacuation. For some of these issues, IMO, International Organization for Standardization (ISO) and International Association of Classification Societies (IACS) provide guidelines in order to clarify the matter on an international basis and contribute to developing appropriate regulations, rules and standards, where necessary.

The following innovative solutions are of instant relevance to fire safety:

1. Special purpose smoke detectors installed in potentially high fire risk spaces, such as inside the galley greasy exhaust ducts, and additional automatic local extinguishing (water-spraying) systems installed in machinery spaces.

2. Automatic/manual means to control the interaction between the smoke extraction, fans, dampers, Heating, Ventilation and Air Conditioning (HVAC) and the fire detection and extinguishing systems.

3. Use of visual display units to simplify and reduce the number of mimic control panels and of audible and visual alarms for monitoring the status of general/fire alarm system, public address system, fire dampers, Hi-Fog system, CO_2 release and alarm system, etc.

The following innovative solutions are of instance relevance to escape and evacuation:

1. Means of escape to avoid bottle necks in corridors and stairways, theatres and atriums designed to accommodate a large number of people, position and dimensions of muster stations evaluated using evacuation analysis.

2. Escape routes designed to fit additional berths in cabins, exceeding the effective total passenger capacity and allowing more flexible booking in relation to clients need.

3. Use of alternative lifesaving appliances to lifeboats, such as chutes and slides associated with life-rafts.

The above mentioned solutions are often based on rules, guidelines and industry standards, which are not compulsory but are instead applied on a voluntary basis.

2.2 Accident Data

The information from international statistical sources shows that main casualty categories are machinery damage, stranding, collision and fire and explosion [Norman, 1997] [Waite & Aston, 1999] [Guillaume, et al., 2003]. Fire accidents have, however, not been reduced to the same extent as the other accident types during the 1988-1991. Fires and explosions have also caused great concern in relation to passenger transport (cruise ships and ferries) [Rensvik, et al., 1994].

The accident data presented in this section are predominantly gathered from the Lloyd's Register [Aldwinckle & Mitchell, 2000]. The LR received 8,744 accident and incident reports of all ships in 2000. Accidents to passenger ships accounted for 457 of those reports. The data presented here is collected from 1990 to 1999 and reflects all the reported incidents and accidents relating to all kinds of vessels.

For all ships losses, in Figure 2.1 shows the 35% of these were caused by machinery and hull damage, 20% by wrecked and stranded, 13% by fire/explosion, 13% by foundered, 11% by collision, 6% by contact and 2% by miscellaneous. Also, the graph indicates that the percentage of each accident events involving the passenger ships. Stranded/wrecked represents 26% of the total losses. Fire risks remain the second largest contributor with 25%, contributing 18% of hull/machinery damage, 11% of contact, 9% of collision, 8% of foundered and 3% of miscellaneous.

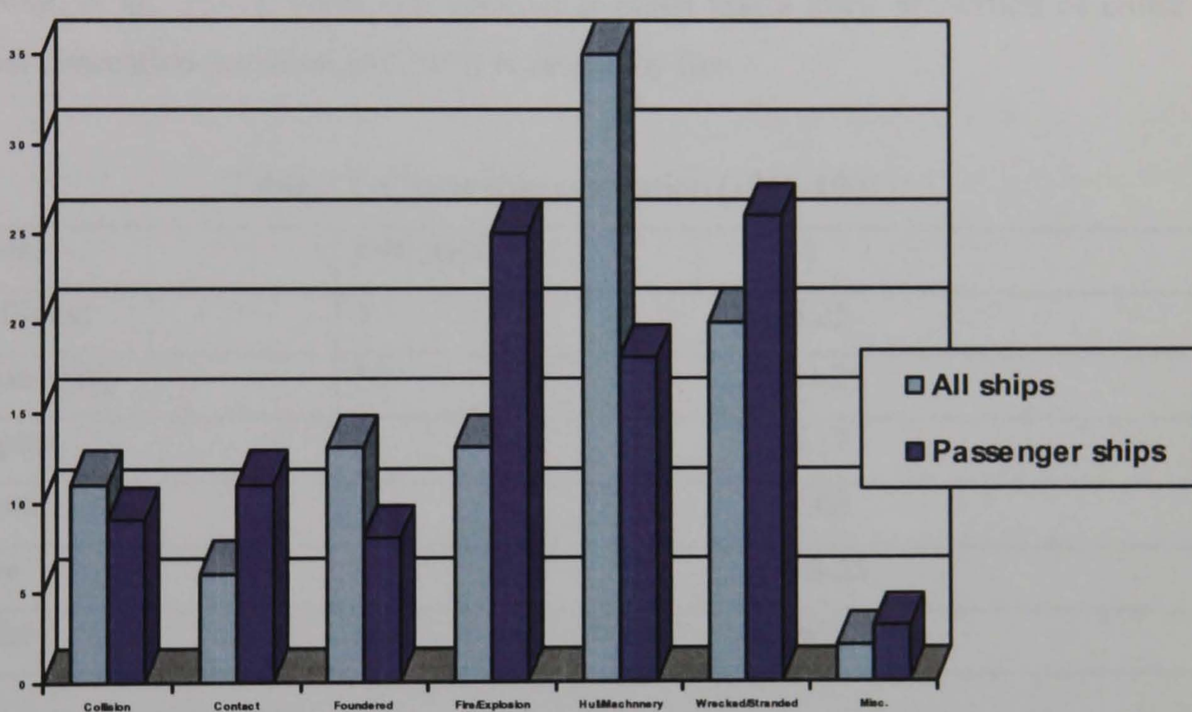


Figure 2.1. Serious casualties ship losses (1990-1999).

To determine the severity of the accidents on cruise ships, data reflecting the accidents to vessels with the fatalities caused are gathered and presented in Table 2.1. This table shows that 51.41% of the total fatalities were caused by collision accidents on vessels and 48.47% by fire accidents [Terje & Arnstein 2000].

Table 2.1. Cruise ship fatalities (1963-1997).

Cause	Fatalities	%
Collision	436	51.41
Grounding	1	0.12
Impact	0	0
Foundering	0	0
Fire	**411**	**48.47**
Total	848	100

Table 2.2 gives the detailed evacuations by accident cause from 1963 to 1997 [Skjong, et al., 1997]. From this table, it is noted that a great proportion of cruise vessel evacuation accidents (56.25%) is caused by fire.

Table 2.2. Cruise ship evacuation (1963-1997).

Cause	Evacuation	%
Collision	3	6.25
Grounding	15	31.25
Impact	2	4.17
Foundering	1	2.08
Fire	**27**	**56.25**
Total	48	100

2.3 Data Analysis

In many cases of the passenger vessel accidents examined, information is incomplete or lacking. This makes it difficult to analyse the events that lead to the accident.

The changes to the SOLAS Convention which had arisen as a result of major accidents such as *Scandinavian Star* (Fire). The Amendments to SOLAS as a result of the *Scandinavian Star* disaster were balanced as follows:

1. 3 amendments preventing fires from starting (6% of regulation changes)

2. 21 amendments preventing fires from escalating (43% of regulation changes)

3. 25 amendments to evacuation arrangements (51% of regulation changes)

It can be reasonably expected that if maritime regulators had been able to agree a proactive approach with the industry, the regulatory effort might have concentrated on the accident initiation and accident escalation prevention stages rather than on mitigation. However it is not possible to take an objective view following a disaster. Survivors accounts of how their escape could have been made easier if particular equipment or systems have been in place cannot be ignored by regulators. The regulator cannot argue against imposing additional safety requirements of little or no value because the regulator has lost credibility as a result of the accident. It is after all difficult to argue that there is little likelihood of a scenario re-occurring if the regulator has failed to predict it in the first case. Also, in the wake of an accident the operator will be represented by corporate spokespersons but making declarations to the effect that 'the operation met every regulatory requirement' often with a subtext that the regulator should have prevented the accident by imposing higher regulatory requirements [Wright, 2000].

It is difficult to state what fire risks are to be counteracted, which measures are the most needed, whether the current measures are effective without a clear definition of the targets of the acceptable, tolerable or unacceptable risks. Answers to these questions can be obtained by applying systematic risk based methodologies aimed at considering the ship's fire safety as a whole, including protection of life, property and the environment, such as the so called Formal Safety Assessment (FSA). The FSA could be useful to identify the most appropriate risk control and mitigation options and to compare different conventional and non-conventional solutions, for instance in terms of their implications on safety and reliability.

However, to become useful, the FSA needs a lot of work to implement all necessary information and tools. It is evident that such an exercise becomes effective if it is carried out on a wide and cooperative basis, with the support of all interested parties, e.g. owners, operators, insurers, administrations, classification societies, etc. FSA will then play an important role in the design and operation of the next generation of passenger ships and offer considerably help to identify the most appropriate fire risk control options relevant to the transport of large numbers of passengers on board these ships.

2.4 Conclusion

A review has been performed on available incident data relevant to passenger vessels. However, the database still lacks sufficient 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 higher than the figures presented here. However, the data gathered and analysed in this chapter show that there is a real problem in the cruise industry. The frequency of fire accidents and the associated severity are still high by maritime standards.

The work in this thesis attempts to provide fire safety assessment methods that could identify the high-risk areas on a passenger ship, thereby justifying and implementing fire risk management solutions. It can be concluded that due to the lack of proper reporting of accidents/incidents on passenger vessels, subjective methods of risk and safety analysis may be more favourable.

References

Aldwinckle, D. & Mitchell, A. (2000), "Guidance from the Assessor: Preparing for the Unexpected", IMarEST International Conference on Safety of Large Passenger Ships – Looking to the Future, Vol 112, Part 2, London, UK, 15-16 May.

Cazzulo, R. & Franciulli, F. (2000), "Safety of Large Passenger Ships Design – A Classification Society's View", IMarEST International Conference on Safety of Large Passenger Ships – Looking to the Future, Vol 112, Part 2, London, UK, 15-16 May.

Guillaume, C., Elisabetta, N., Franco, Z. & Carlo, E. (2003), "Safety First Project Probabilistic Models and Data", RINA International Conference on Passenger Ship Safety, London, UK, 25-26 March.

IMO (1999), "Enhancing the Safety of Large Passenger Ships", Maritime Safety Committee, Work Programme, MSC 72/21, London, UK.

Norman, H. (1997), "Maritime Casualties: 1963-1996", 2nd Edition Book, Informa (Lloyd's of London Press), May.

Rensvik, E., Mørkve, O. T. & Kristiansen, S. (1994), "Development of An Integrated Fire-fighting System", IMarEST International Conference on Fire Safety on Ships – Developments into the 21st Century, IMAS 94, London, UK, 26-27 May.

Skjong, R., Adamcik, P., Eknes, M. L., Gran, S. & Spouge, J. (1997), "Formal Safety Assessment of Helicopter Landing Area on Passenger Ships as a Safety Measure", DNV Report 97-2053 (Available as IMO/COMSAR 3/2), Norway.

Terje, S. & Arnstein, E. (2000), "Complexity of Safety Considerations with Large Passenger Vessels", IMarEST International Conference on Safety of Large Passenger Ships – Looking to the Future, Vol 112, Part 2, London, UK, 15-16 May.

Waite, J. B. & Aston, J. G. L. (1999), "Do We Ever Learn? – The Perspective of the Salvage Association", RINA International Conference on Learning from Marine Incidents, London, UK, 20-21 October.

Wright, D. (2000), "The Safety of Large Passenger Vessels: Guidance from the Regulator?", IMarEST International Conference on Safety of Large Passenger Ships – Looking to the Future, Vol 112, Part 2, London, UK, 15-16 May.

CHAPTER 3 – SAFETY ANALYSIS METHODS AND FORMAL SAFETY ASSESSMENT (FSA) OF A GENERIC PASSENGER VESSEL

Summary

This chapter gives a detailed review of some of the typical safety analysis techniques (including fire modelling and evacuation modelling techniques) currently in use. Each method's characteristics are investigated. The FSA approach is described and discussed in the context of a trial application to a generic passenger vessel.

3.1 Safety Analysis Methods

3.1.1 Introduction

When studying the safety aspects of a large ship, it is almost impossible to treat the system in its entirety. A logical approach may be to break down the system into functional entities comprising subsystems and components. Safety modelling of these functional entities can be carried out in such a logical structure, then the interrelationships can be examined and finally a system safety model can be formulated to assess the safety parameters. The formulation of a system safety model can be difficult for a large and sophisticated marine system and thus requires approximations and judgement [Pillay & Wang, 2003].

It is very beneficial to apply safety analysis methods effectively and efficiently in the design for safety process. This chapter specifies how to deal with such problems. This requires an understanding of the concepts of qualitative and quantitative safety analysis.

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 four questions:

1. What can go wrong?
2. How likely are the potential problems to occur?
3. How severe might the potential problems be?
4. What lessens can/should be learn from the risk?

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 fifth question to be answered:

5. 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.

3.1.2 Qualitative and quantitative safety analysis

Depending on the requirements of safety analysts and the safety data available, either a qualitative or a quantitative analysis can be carried out to study the risks of a system in terms of the occurrence probability of each hazard and its possible consequences. A severe hazard with a high occurrence probability requires priority attention and a hazard which is not likely to occur and which results in negligible consequences usually requires minimal attention [Aldwinckle & Pomeroy, 1983].

3.1.2.1 Qualitative safety analysis

Qualitative safety analysis is used to locate possible hazards and to identify proper precautions (design changes, administrative procedures, etc.) that will reduce the frequencies or consequences of such hazards. It should become an integral part of the marine design process. It may be performed with one or more of the following objectives [Pillay & Wang, 2003]:

- To identify hazards in the design.
- To document and assess the relative importance of the identified hazards.
- To provide a systematic compilation of data as a preliminary step to facilitate quantitative analysis.
- To aid in the systematic assessment of the overall system safety.

Engineering judgement and past experience are required to carry out a qualitative safety analysis. Measures can be taken to eliminate or control hazards based on the information produced from qualitative safety analysis.

3.1.2.2 Quantitative Risk Analysis (QRA)

QRA is a valuable tool to establish valid and more precise relationships between the costs of safety, maintenance, etc. and the benefits of maintaining production in a safe and ecologically acceptable environment. These relationships can be used to compare and evaluate different risk scenarios and different design or mitigation proposals so that designs and operating procedures can be optimised to meet commercial requirements and external standards at minimum cost. This leads to more realistic, moderate and efficient conclusions than analysis based on regulations only, where the issues are only good (if the regulation is applied) or bad (if not applied) [SAFERRELNET, 2002].

Although QRA started in the nuclear and chemical process industries, the combined effects of commercial pressure, statutory regulation, and public concerns mean that increasingly it is seen to be of benefit, or at least potential benefit, in other industries and activities.

The purpose of QRA is to describe the risk by a value that is measurable with criteria or other values associated with an operation and design. Risk is a multi-dimensional concept involving hazard frequency and its consequences. QRA involves the estimation of the frequency and consequences of a range of hazard scenarios and of individual and societal risk (or economical risk). QRA is normally a part of a risk assessment. The risk assessment process is depicted in Figure 3.1 [Lee, 1996].

The purpose of risk assessment based on QRA is normally to [SAFERELNET, 2002]:

- Assess the risk of fatality or serious injury to persons (workforce or the members of the public).
- Identify measures to reduce the overall risk and assess the effectiveness of such measures.
- Assist in the selection of preferred options for enhanced safety.
- Assist in the setting of Performance Standards for design, monitoring and audit purposes.
- Assist cost benefit assessment of possible safety expenditure.
- Assist in decision making on whether the risk is tolerable against the risk acceptance criteria.
- Assess the environmental risk.
- Assess the risk to the asset and / or revenue.

The results of a QRA may not be precise and this should be recognised when they are used for making decisions. This is not that important when comparing several designs, but it can lead to substantial problems when the aim is to assess absolute figures. Therefore, QRA results should always be carefully reviewed in the context of the specific circumstances of a particular decision or requirement. There is no standardised method for carrying out a QRA.

Sensitivity to variations in the assumptions made should be checked to provide an indication of the criticality of the input data. Where necessary, a more detailed analysis of the most critical data should be conducted to improve the confidence in the results.

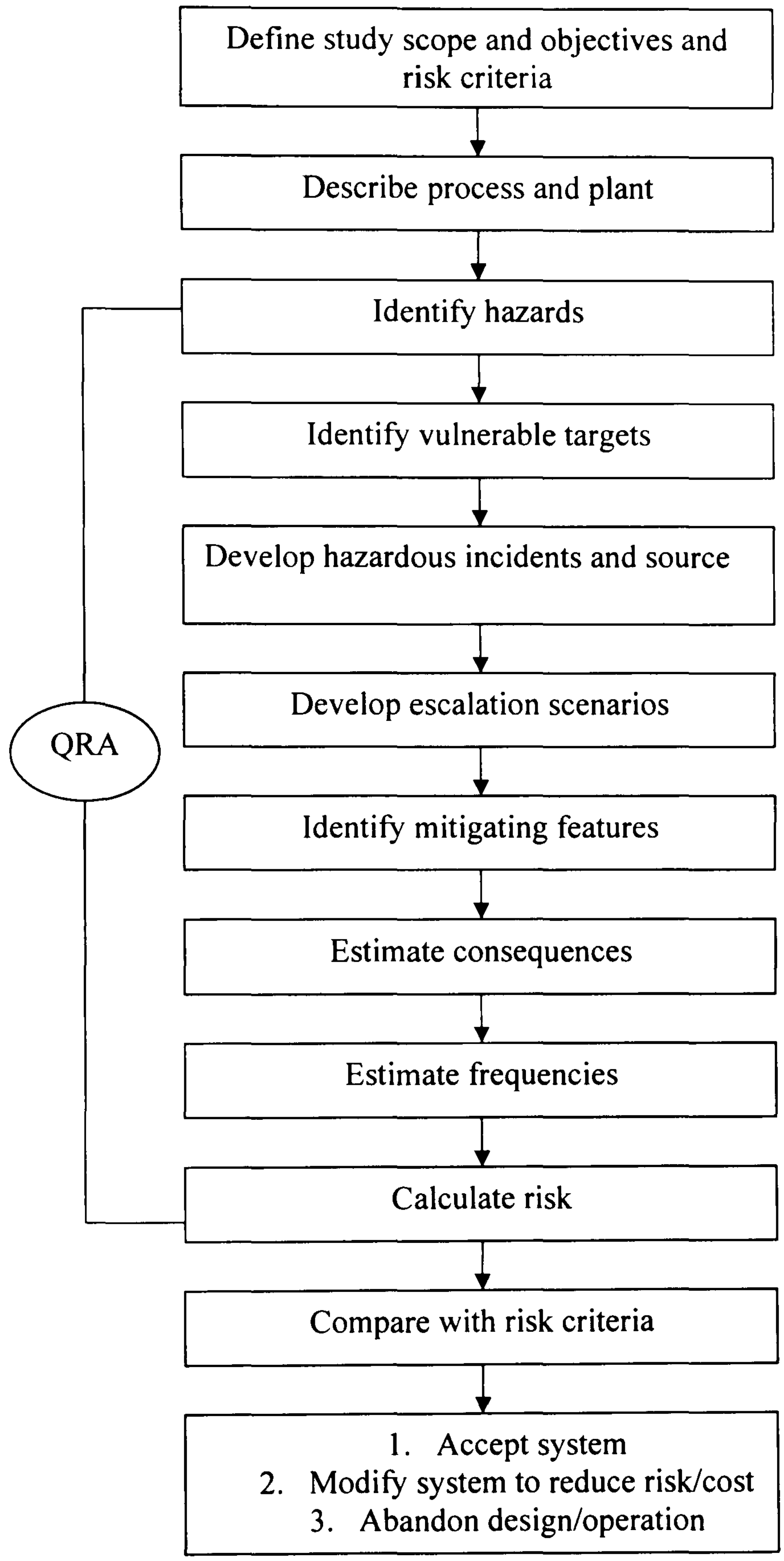


Figure 3.1. QRA with the risk assessment process [Lee, 1996].

The typical methods used in a QRA to estimate the risk are:

- Event Tree Analysis (ETA).
- Fault Tree Analysis (FTA).
- Cause-Consequence Analysis (CCA).
- Failure Mode, Effects and Criticality Analysis (FMECA).
- Risk Matrix Approach.
- Fuzzy Sets Theory.

3.1.2.2.1 Event Tree Analysis (ETA)

ETA utilizes decision trees to graphically model the possible outcomes of an initiating event capable of producing an end event of interest. This type of analysis can provide (1) qualitative descriptions of potential problems (combinations of events producing various types of problems from initiating events) and (2) quantitative estimates of event frequencies or likelihoods, which assist in demonstrating the relative importance of various failure sequences [Henley & Kumamoto, 1996] [Villemuer, 1992]. ETA may be used to analyze almost any sequence of events, but is most effectively used to address possible outcomes of initiating events for which multiple safeguards are in line as protective features [ABS, 2003].

An example of a simple Event Tree (ET) is shown in Figure 3.2. The fire protection is provided by a sprinkler system. A detector will either detect the rise in temperature or not. If the detector succeeds the control box will either work correctly or not - and so on. There is only one branch in the tree that indicates that all the subsystems have succeeded.

The ET that calculates the outcomes of the scenario will be more detailed in Chapter 4.

3.1.2.2.2 Fault Tree Analysis (FTA)

Compared to an ET the Fault Tree (FT) analysis works in the opposite direction. It is a deductive approach, which starts from an effect and aims at identifying its causes. Therefore a FT is used to develop the causes of an undesirable event. It starts with the event of interest, the top event, such as a hazardous event or equipment failure, and is developed in a top down manner [SAFERRELNET, 2002].

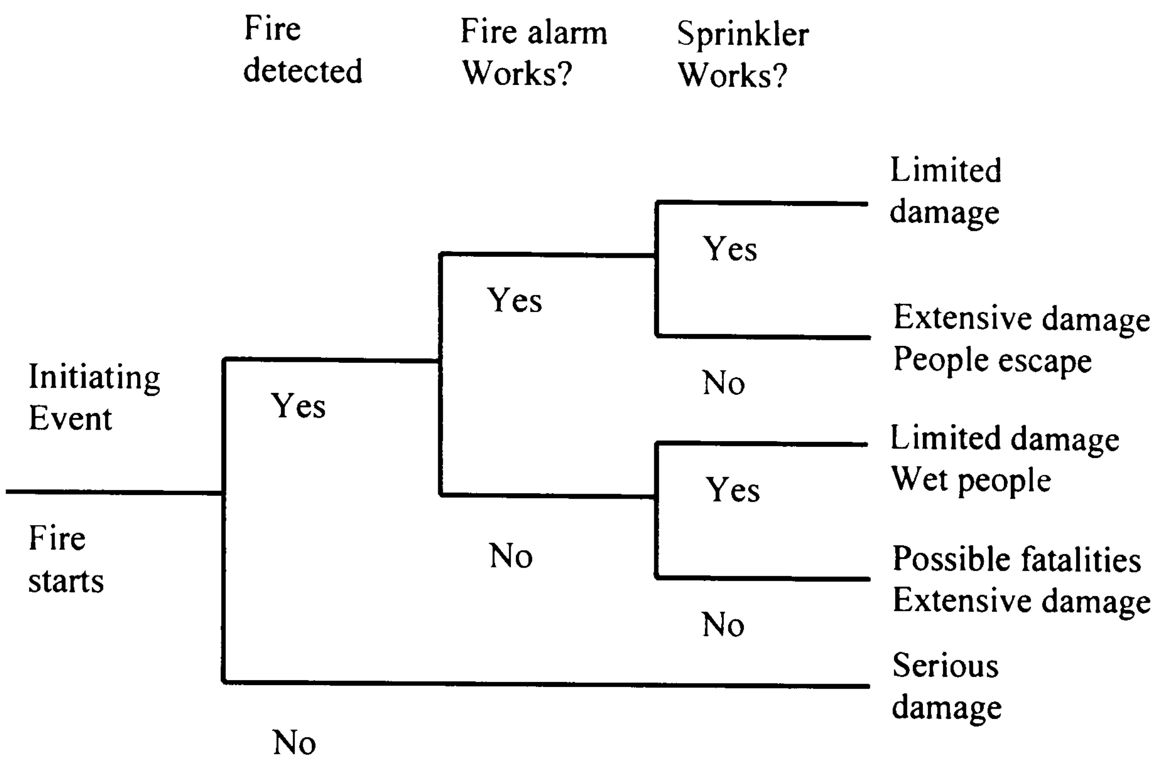


Figure 3.2. A simple ET structure.

FTA is both a qualitative and a quantitative technique. Qualitatively it is used to identify the individual scenarios (so called paths or cut sets) that lead to the top (fault) event, while quantitatively it is used to estimate the probability (frequency) of that event.

A component of a FT has one of two binary states, either in the correct state or in a fault state. In other words, the spectrum of states from total integrity to total failure is reduced to just two states [SAFERRELNET, 2002].

A FT is basically a graphical representation of the Boolean (logical) equation which links the individual component states to the whole system state. Therefore, it encompasses all the possible states of the whole system. These states are split into two classes according to that the top event is achieved (true) or not (false).

The basic elements of a FT may be classed as (1) the top event, (2) primary events, (3) intermediate events and (4) logic gates.

An example of a simple FT with an "AND" gate and an "OR" gate, is shown in Figure 3.3.

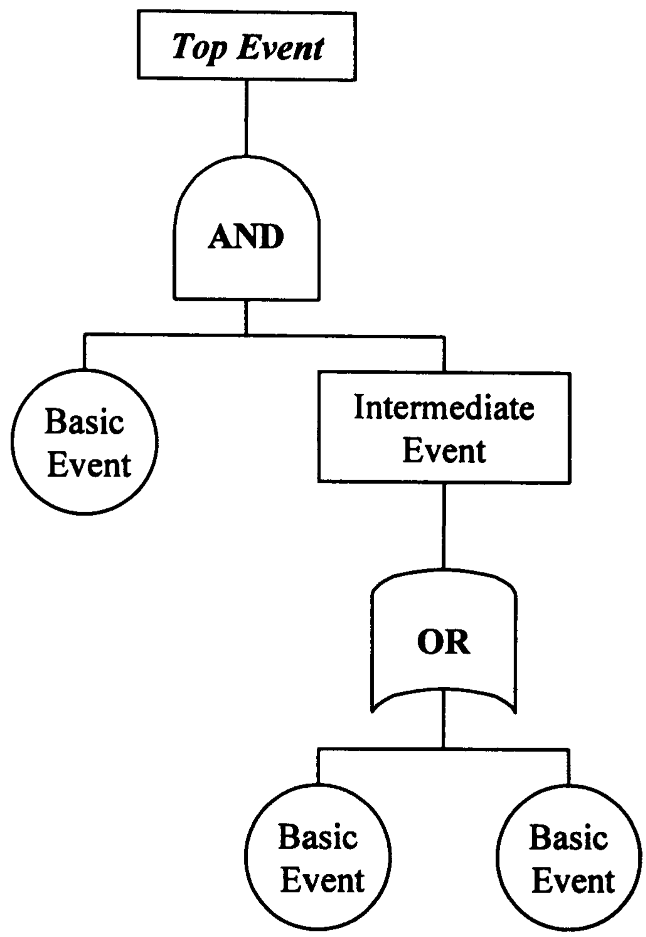


Figure 3.3. Fault Tree example.

There are several benefits of employing FTA for use as a safety assessment tool. These include:

- 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 & Moss, 2002].
- 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.

3.1.2.2.3 Cause–Consequence Analysis (CCA)

CCA is a marriage of fault tree analysis (to show causes) and event tree analysis (to show consequences). CCA is a diagrammatic approach as shown in Figure 3.4. Construction of cause-consequence diagrams starts with a choice of a critical event. The "consequence tracing" part of a CCA involves taking the initial event and following the resulting chains of events through the system. The "cause identification" part of a CCA involves drawing the fault tree and identifying the minimal cut sets leading to the identified critical event. CCA is extremely flexible as it can work forward using event trees and backward using fault trees [Pillay & Wang, 2003].

Such a cause-consequence diagram is easy to modify and it can be split in several sub-diagrams. As such, CCA is a realistic and efficient tool to analyse a new system or a new procedure. It is a means to gather in a practical way several FTs and it is possible, when it has been built completely, to easily derive an equivalent ET.

3.1.2.2.4 Failure Mode, Effects and Criticality Analysis (FMECA)

FMECA is probably the most widely applied hazard identification method. It is a combination of Failure Mode and Effects Analysis (FMEA) and Criticality Analysis (CA). It can be carried out at any indenture level required to examine each failure mode of an item and its possible consequences.

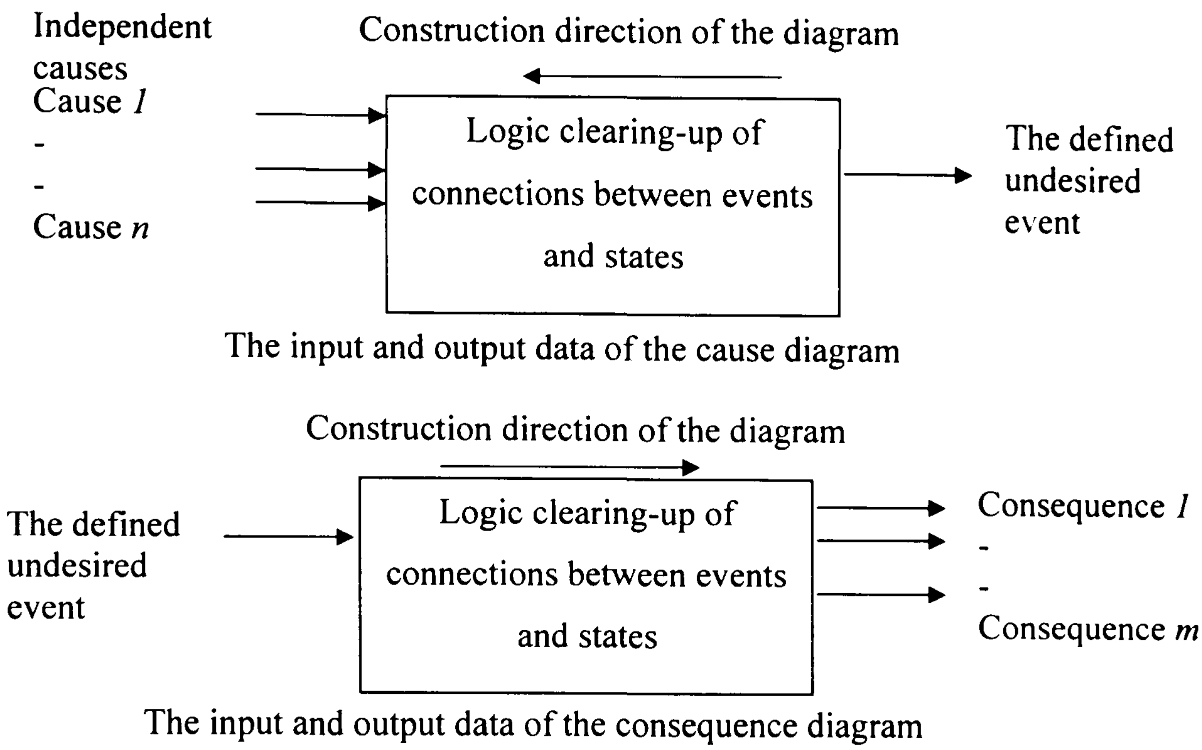


Figure 3.4. The diagram of cause-consequence analysis.

The objectives of a FMECA are:

1. Identification of each failure mode, of the sequence of events associated with it and of its causes and effects.
2. A classification of each failure mode by relevant characteristics, including detectability, diagnosability, testability, item replaceability, compensating and operating provisions.
3. An assessment of the criticality of each failure mode.

An FMECA may consist of the following steps [MIL-STD-1629A, 1980]:

- Define the constraints and assumptions of the analysis.
- Break down the system to its indenture levels such as the sub-system level and the component level.
- For each item at the level analysed, identify all possible modes of failures and respective causes.
- For each identified failure mode, identify or provide the following information:
    1. All the distinctive operating conditions under which failure may occur.

2. The failure rate of the identified failure mode.

3. The effects (consequences) on the safety and operability of the higher levels (including the level analysed).

4. The possible means by which failure may be identified.

5. Design provisions and/or actions in operation to eliminate or control the possible resulting effects.

6. The severity class of the possible effects where such a class may be defined by one of the following linguistic variables:

Catastrophic:	Involving death, system loss and/or severe environmental damage.
Critical:	Involving severe injury, major system damage and/or major environmental damage.
Marginal:	Involving minor injury, minor system damage and/or minor environmental damage.
Negligible:	Involving no injury and negligible damage to the system and the environment.

- Failure consequence probability defining the likelihood that the effects of the identified failure mode will occur, given that the failure mode has taken place.

- Criticality analysis

Criticality analysis allows a ranking of the criticality of the failure modes of items as a function of the severity classification and occurrence likelihood.

If the probability of occurrence of each failure mode of an item can be obtained from a reliable source, the criticality number of the item under a particular severity class may be quantitatively calculated as follows:

$$C = \sum_{i=1}^{N} E_i L_i t$$

where: C = criticality number,

E_i = failure consequence probability of failure mode i,

L_i = likelihood of occurrence of failure mode i,

N = the number of the failure modes of the item, which fall under a particular severity classification, and

t = duration of applicable mission phase.

Once the criticality numbers of the item under all severity classes have been obtained, a criticality matrix can be constructed which provides a means of comparing it to all other items. Such a matrix display shows the distributions of criticality of the failure modes of the item and provides information for assigning priority for corrective action. Criticality analysis can be performed at different levels. Information produced at low levels may be used for criticality analysis at a higher level.

An FMECA is an inductive process which involves the compilation of reliability data, where available, for individual items. Information produced from FMECA may be used to assist in construction of fault trees and also in construction of Boolean representation tables [Wang, et al., 1995].

3.1.2.2.5 Risk matrix approach

The early form of the risk matrix methodology was presented in the [MIL-STD-882, 1969]. This methodology has founded wide application in many areas of technology.

The proposition of quantitative risk assessment presented to ships, which was based on the risk matrix methodology [Kobyliński, 1997]. The following definition was assumed: "Risk is defined as hazard probability times hazard severity (consequences)". In generally used terminology risk means the product of the probability of accident occurrence and the severity of damages being the results of accident.

Further, the ordered two define the risk category: the level of probability and the category of severity. The risk acceptance can be determined on the set of these two (e.g. intolerable risk, As Low As Reasonably Practicable (ALARP) and negligible risk).

Data needed to risk assessment by the risk matrix methodology can be obtained from the historical records of the analysed system, similar systems or from expert judgements.

The risk matrix approach will be evaluated and used in Chapter 3.2.4 and Chapter 4.

3.1.2.2.5.1 Risk acceptability criteria

Acceptance of risk is basically a problem of decision making, and is inevitably influenced by many factors such as type of activity, level of loss, economic, political, and social factors, confidence in risk estimation, etc. A risk estimate, in the simplest form, is considered acceptable when below the level which divides the unacceptable from acceptable risks. A better description of risk criteria is as the standards which are used to translate risk estimates as produced by a risk analysis into value judgements.

As far as risk criteria for ships are concerned, the general criteria may include [Spouse, 1997]:

1. The activity should not impose any risks which can reasonably be avoided.
2. The risks should not be disproportionate to the benefits.
3. The risks should not be unduly concentrated on particular individuals.
4. The risks of catastrophic accidents should be a small proportion of the total.

More specifically, individual risk criteria and social risk criteria need to be defined. For example, an estimate of individual risk per annum of 10^{-7} can be considered as "negligible risk"; similarly, an estimate of injuries occurring several times per year, can be considered as "unacceptable" [Pillay & Wang, 2003].

In addition to the risk matrix, i.e. the boundaries of risk acceptability and intolerability, risk criteria, in general, contain recommendations on the tolerability of the overall system risk and the extent to which taking further risk reducing measures may be justified.

3.1.2.2.6 Fuzzy sets theory

Problems of uncertainty in safety analysis can be treated using two principal types of methods involving probability and possibility, respectively. Probability methods deal with uncertainty which is essentially random in nature but of an ordered kind. Probabilistic methods are based on a mature scientific theory [Apostolakis et al., 1993]. Possibility methods (non-probabilistic methods) study problems which are not really probabilistic but cause uncertainty due to imprecision associated with the complexity of a system as well as vagueness of human judgement. Possibility methods often use fuzzy sets, possibility theory and belief functions [Apostolakis et al., 1993].

In probabilistic risk assessment, probability distributions are used to describe a set of states for a system and to deal with uncertainty in order to evaluate potential hazards and assessment system safety. In many cases, however, it may be difficult or even impossible to precisely determine the parameters of a probability distribution for a given event due to lack of evidence or due to the inability of the safety engineer/designer to make firm assessments. Therefore one may have to describe a given events in terms of vague and imprecise descriptors such as "*likely*" or "*impossible*", terms that are commonly used by safety analysts/designers. Such judgements are obviously fuzzy and non-probabilistic, and hence non-probabilistic methods such as fuzzy set modelling may be more appropriate to analyse the safety of systems with incomplete information of the kind described above.

Fuzzy set modelling can also be used together with Multiple Attribute Decision-Making (MADM) methods to assist decision makers in selecting the winning design/procurement proposal that best satisfies the requirement in hand. It can also be used together with Analytical Hierarchy Process (AHP) and the Delpli method in carrying out design support evaluation [Sii et al., 2002].

In maritime risk assessment, the application of numerical risk criteria may not always be appropriate because of uncertainties in inputs [Wang & Kieran, 2000].

Accordingly, acceptance of a safety case/a formal safety assessment is unlikely to be based solely on a numerical assessment of risk. In situations where there is a lack of safety data for analysis or the level of uncertainty in safety data is unacceptably high, fuzzy set modelling may be effectively used as a useful alternative approach by maritime safety analysts to facilitate risk modelling and decision making.

3.1.3 Fire safety modelling

Zone models have been used since the mid 1970s to predict thermal hydraulic conditions in a fire compartment prior to flashover. The zone model approximation treats the compartment atmosphere as two well mixed layers, namely a hot smoky layer above a cooler and clearer layer. Such stratification often arises as a result of buoyancy, but may be inapplicable in certain situations such as tall stairwells, long corridors, or other situations where three dimensional effects are important. Zone models apply conservation equations to each layer, with the user specified fire providing a source of energy and mass.

Fire-growth And Smoke Transport (*FAST*) is a zone model developed by the US National Institute of Standards and Technology (NIST) to predict the smoke layer interface height, layer temperatures, surface temperature and combustion product concentrations during a fire in an enclosed space [Walter & Richard, 1989].

The aspects covered include:

1. Multiple connected compartments.
2. Multi fires (constrained or unconstrained).
3. Vertical and horizontal vents.
4. Mechanical ventilation.
5. Conduction through surfaces.
6. Radiation between fire, layers and surfaces.
7. Combustion chemistry and resulting toxic concentrations and optical density.
8. Attenuation by sprinklers.

At the outset, it is important to note that *FAST* is intended for use only by those competent in the field of fire safety and is intended only to supplement the informed judgment of the qualified user. The software is intended to provide quantitative estimates of some of the likely consequences of a fire. The model has been subjected to a range of verification tests to assess the accuracy of the calculations. Like any computer calculation, however, the quality of the calculated result is directly related to the quality of the inputs provided by the user. Lack of accurate predictions by the model could lead to erroneous conclusions with regard to fire safety. All results should be evaluated by an informed user.

SMARTFIRE has been developed at the University of Greenwich using a combination of in-house and proprietary software building blocks [Wang, et al., 2001]. The software produces reasonable agreement with experimental temperature measurements derived for a non-spreading fire in a moderately large ventilated fire compartment. The coarse mesh simulation, while performed on a relatively crude computational mesh is able to represent the broad features of qualitative trends in the observed temperature distributions at the locations quantitatively, temperatures are generally over-predicted and the level of stratification within the compartment is not well represented.

LUCIFER enables a deterministic appreciation of the step-by-step propagation of a fire after a set time 't'. It also enables the identification of vital functions that will be partially or totally destroyed and important zones affected by the fire [Garsmeur & Anselme, 1998]. The time parameter 't' corresponds to the sum of the detection time and the time needed for the fire crew to contain the fire, in other words to prevent it spreading. *LUCIFER* does not calculate the fire duration through to its extinction by quenching, lack of combustible material or through the action of fixed or mobile fire-fighting equipment within the volume formed by the burning zones.

3.1.4 Evacuation modelling

The computer simulation models for evacuation analysis that have appeared over the last two decades have marked the evolution of evacuation models from 'hydraulic' and/or 'ball-bearing' models to behavioural models with adaptive capabilities, which can be represented as a *simplified method* and an *advanced method*. Today, over 40 different evacuation models for aircraft, building, trains and ships exist. While each model is very different, they all share common approaches in the way they represent the geometrical environment, i.e. the configuration of the structure, the population and the behaviour of evacuating individuals. These three constituent components are pivotal in defining the nature of an evacuation model [Sharp, et al., 2003]. Within the modelling methodologies adopted, there are a number of ways in which to represent the geometry, population and behaviour of the evacuees. To a certain extent, the range of models reflects the purpose for which they were originally intended, the nature of the developers, and also the availability of computing power at the time of the development. In the following an attempt is made to review the computer-based implementations of modelling approaches that are widely accepted as applications to be used in the maritime environment.

SIMULEX was originally developed at the University of Edinburgh and is currently maintained by IES Scotland. *SIMULEX* is a model that through the use of a detailed spatial representation, concentrates on the physical aspects of the population and the way these affect the outcome of the evacuation. It intended to be used as a design tool by fire safety engineers and possibly architects and building engineers when devising the geometric layout of buildings in the design stages [Thompson, et al., 1995a, 1995b, 1996]. *SIMULEX* can be used to simulate the evacuation of large number of people from large multi-floored structures.

EVACSIM and *EVAC* are both discrete time step models. *EVACSIM* was developed in 1995 and has been used to model and analyse the evacuation flow for public and private facilities (including buildings, stadiums, passenger terminals and offshore oil platforms) [Soma, et al, 1995]. *EVAC* was developed to comply with IMO regulations in addition to Norwegian regulations, which are considerably stricter [Drager & Orset, 1999]. *EVAC* is a model that applies a coarse network method of geometry representation. This would be supported in that passengers escape via means of an escapeway, which is a series of linked decision points

maritimeEXODUS is part of the *EXODUS* suite of software tools based on an automatic model developed by the Fire Safety Engineering Group (FSEG) at the University of Greenwich. [Galea, et al., 1996, 1999] [Owen, et al., 1996, 1998]. The suite also exists for use in buildings and aircraft (for aircraft design and certification). Recently, FSEG is extending the system for application of marine fields. In collaboration with the Canadian company Fleet Technology and the Canadian government, a detailed abandonment model is currently under development and a series of full-scale trials is being developed in order to collect human performance data under different conditions of list. This information will be incorporated with *maritimeEXODUS* along with appropriate modifications to the behaviour sub-model. The current prototype version of *maritimeEXODUS* does not posses marine specific data for the performance of passengers under conditions of list and roll. However, when this data is available it can easily be incorporated into the model framework. As the model has the flexibility to allow the user to alter the entire preset default values, it is easily adaptable when new data becomes available. Furthermore, the current version of *maritimeEXODUS* does not include reliable data to represent the preparation/ deployment of the escape system or the actual abandonment of the vessel. Again, these aspects can be included when data become available.

Evacuability index (Evi) was developed by the Ship Stability Research Centre (SSRC) at the Unversities of Glasgow and Strathclyde [Vassalos, et al., 2001]. *Evi* is passenger evacuation software developed specifically for a ship-sea environment, capable of real time evacuation simulation of the most complex of scenarios in the largest cruise ships. It represents the state-of-the-art computer simulation-based capability for the prediction of passenger mustering and evacuation involving a number of escape and rescue scenarios (abandon ship, transfer to refuge centres or a combination of these) in a range of incidents (fire, collision, progressive flooding, cargo shift, foundering) whilst accounting for ship motions in a sea environment. Valuable input and feedback from the owners/operators can help refine and render the model a practical tool which, coupled to modelling of uncertainty in all the parameters that may affect evacuation times and the ability to play back a given scenario as video.

provides the analyst with wide-ranging capability in modelling realistically the most complex of evacuation scenarios thus allowing for routine applications of passenger evacuation analysis. The latter entails a wide range of evacuation capabilities including evaluation of evacuation time, potential bottlenecks, assessment of accommodation module layout and sensitivity analyses to assist design for ease of evacuation, passenger familiarisation with a ship's environment, "what if" scenarios for training, devising effective evacuation planning procedures/strategies and decision support to manage a crisis. *Evi* is available in the form of a computer program that can be readily customised to any vessel environment with an efficiently tailored user interface and Run Time Simulator (RTS).

3.1.5 Discussion

In this section, typical safety analysis methods, fire modelling and evacuation modelling techniques 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 passenger vessel fire safety assessment may not be as straightforward as it may seem. Certain modifications are needed to enhance the application of such methods to passenger ships. 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 individually or in a combined manner within the framework of a Formal Safety Assessment (FSA) process. The FSA process will be described and discussed in the next section, detailing how the analysis methods outlined can be used effectively together with some of the novel techniques developed in the following chapters of this thesis.

3.2 Formal Safety Assessment (FSA)

3.2.1 Introduction

Traditionally, improvements in shipping safety have emerged in response to major accidents. Under FSA, the International Maritime Organisation (IMO)'s approach to regulation would aim to anticipate accidents through risk assessment and set standards accordingly. The loss of the Alexander Kielland semi-submersible and the Piper Alpha platforms focussed enormous attention on the unsatisfactory system which had seen such structures built to comply with existing rules, but which had been unable to prevent disasters costing several hundred lives [Department of Energy, 1992].

The Cullen inquiry [Department of Energy, 1992] into the loss of the Piper Alpha, in the UK sector of North Sea firmly committed the offshore industry to altering its design approval process to embrace formal safety assessment and the safety case. The offshore operators have to demonstrate that each of their installations complies not only with prescriptive rules, but also meets certain levels of safety. It is an expensive and time consuming process, but against the public perceptions of offshore safety. It has been heightened by the huge publicity of the Piper Alpha disaster, which clearly left no choice for the industry.

In 1992, the Select Committee of the House of Lords published a report entitled 'Safety Aspects of Ship Design and Technology' [House of Lord, 1992]. The report called for a more scientific approach to ship safety, with an emphasis on performance or goal-based rather than prescriptive requirement or the so called safety case regime.

The UK government responded to the report agreeing that the concept was ideal to be worked towards but recognising that it was not a practicable solution at present. However, the UK recognised that a number of elements of the safety case approach were being progressed, such as the introduction of the International Safety Management (ISM) Code and a move towards greater use of performance based regulations both at IMO and in Classification Society Rules. As a result, the UK submitted a paper to the IMO Maritime Safety Committee drawing on the conclusions of the House of Lords Report encouraging the application of the safety case approach to the work of IMO and to shipping. In order to distinguish the approach as applied to ships from elsewhere the paper used the term FSA [Sii, 2000]. This is a new approach to maritime safety which involves using the techniques of risk assessment and cost-benefit assessment, not for individual ships, but as a basis for IMO's rule making process for shipping in general. The UK reasoned that the adoption of FSA would enable safety issues at IMO to be prioritised, and regulations derived that are cost effective and proportional to risk.

FSA was seen by the UK in its proposal to the Maritime Safety Committee as comprising five steps as follows: identification of hazards; assessment of risks associated with those hazards; ways of managing the risks identified; cost benefit assessment of the options identified in the previous step; and decisions on which options to select [Peachey, 1995]. FSA is designed for application to common safety issues for a generic vessel type. In this section, a trial application of the proposed formal risk analysis techniques together with the FSA approach to a generic passenger vessel is demonstrated.

3.2.2 Formal Safety Assessment (FSA)

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. The FSA is based on QRA and provides applications of QRA to marine transportation. It is a structured methodology, aimed at enhancing maritime safety, including protection of life, health, the maritime environment and property.

FSA is thought as a tool to help in the evaluation of new regulations for safety in shipping and in comparisons between existing and possibly improved regulations. It can be applied by Governmental Administrations and Organisations when proposing amendments to safety. It is possible to apply the FSA on the level of classification societies, shipyards and ship owners.

International teams have been developing FSA continuously. The "Interim Guidelines for the Application of Formal Safety Assessment to the IMO Rule –Making Process" was produced in 1997 [IMO, 1997a], and the "Draft Guidelines for FSA" was revised in 2001 as the report of the Correspondence Group [IMO, 2001a, 2001b]. The state-of-art report is based on the latter guidelines.

3.2.3 Basic terminology of FSA

The following basic terminology is used within FSA [Wang, 1994]:

Accident	An unintended event involving fatality, injury, ship loss or damage, other property loss or damage, or environment damage.
Accident category	A designation of accident reported in statistical tables according to their nature, e.g. fire, collision, grounding, etc.
Accident scenario	A sequence of events from initiating event to one of final stages.
Consequence	The outcome of an accident.
Frequency	The number of occurrences per unit time (e.g. per year).
Generic model	A set of functions common to all ships or areas under consideration.
Hazard	A physical situation with a potential for human injury, damage to property, damage to the environment or some combination of these.
Initiating event	The first event of the sequence leading to a hazardous situation or accident.
Risk	The combination of the probability and the degree of the possible injury or damage to health in a hazardous situation.
Risk contribution tree	The combination of all fault trees and events trees that constitute the risk model from hazard to outbreak of the categories and sub-categories of accidents.
Risk control measure	A means of controlling a single element of risk.
Risk contribution option	A combination of risk control measures.
Risk evaluation criteria	Criteria used to evaluate the acceptability /tolerability of risk.

3.2.4 Methodology of FSA

FSA methodology comprises the following five steps:

- Step 1: Identification of hazards.

- Step 2: Estimation of risk associated with those hazards.

- Step 3: Development and evaluation of alternative ways of managing those risks, which need to be addressed.

- Step 4: Cost benefit assessment of these alternative risk management options.

- Step 5: Decision making and recommendations.

The flow chart between these steps is presented in Figure 3.5. The purpose in Step 1 is to identify and generate a prioritised list of hazards, specific to the problem under consideration. Hazard identification comprises both creative and analytical techniques. The first one should ensure that the identification process is proactive, directed not only to the past but also to the events possible in the future. It is carried out by the group of experts of various appropriate areas (design, operation, management, safety analysis) during structured reviews. The combination of available data and judgements is usually used. The review session may last over a number of days. The analytical techniques ensure that the previous experience is properly taken into account. A coarse analysis of possible causes and outcomes of each identified accident category is made by using standard techniques (ETA, FTA, CCA, and FMECA, etc.).

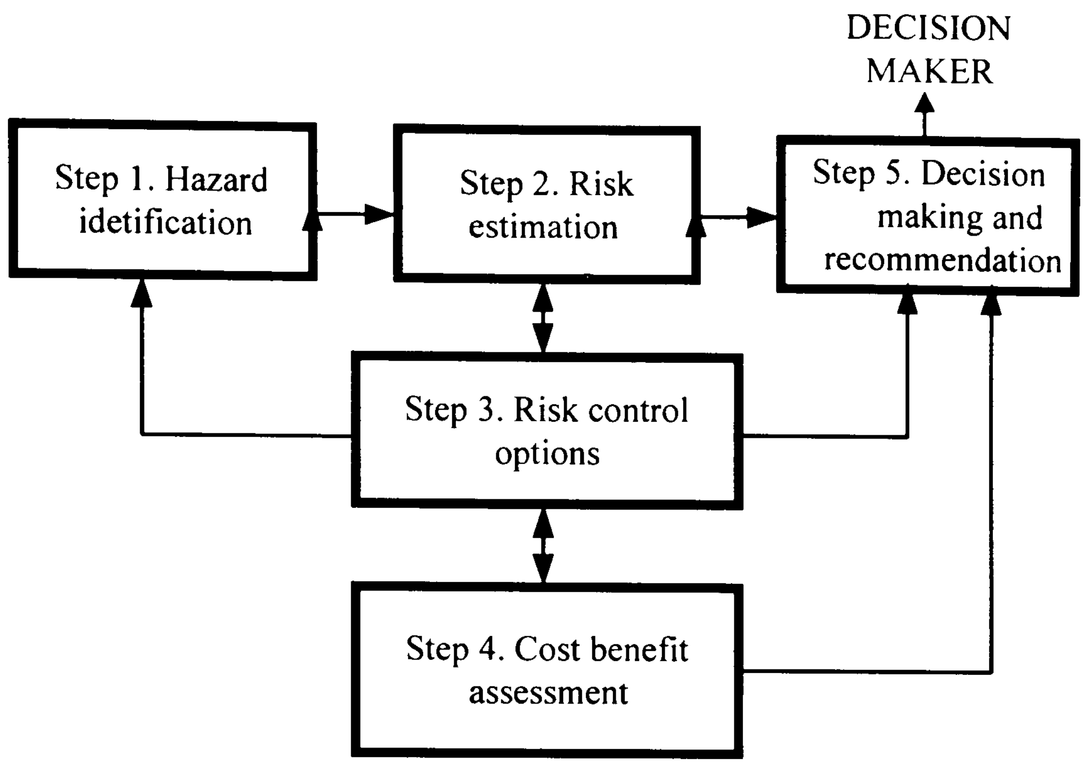


Figure 3.5. FSA methodology [IMO, 1997a].

3.2.5 An example

Using the risk matrix approach the screening of earlier identified hazards is carried out. The available data on the frequency about different outcomes of accident scenarios, supported by judgements, are used. The risk matrix and connected taxonomies are shown in Tables 3.1-3.3 [IMO, 1997b]. The consequence and probability indices used in the matrix are determined in logarithmic scale. A risk index may therefore be established by adding the probability/ frequency and consequence indices (risk is defined as the product of probability and severity of a damage).

The purpose in step 2 is to estimate the distribution of risk, obviously connected with the hazards, which were identified and selected in step 1, and to address high risk areas. Risks to people, the environment and property are considered in dependency on the issue under analysis.

Table 3.1. Frequency indexes.

Fi	Frequency (Likelihood of occurrence of a single event a vessel)	General interpretation
F1	10,000 – 100,000 years	Extremely remote to extremely improbable
F2	1,000 – 10,000 years	Remote to extremely remote
F3	100 – 1,000 years	Remote
F4	10 – 100 years	Reasonably probable to remote
F5	1 to 10 years	Reasonably probable
F6	Yearly	Reasonably probable
F7	Monthly	Frequent

Table 3.2. Severity indexes.

Si	Severity	Effects on human safety	Effects on ship
1	Minor	Minor injuries	Local equipment damages
2	Significant	Major injuries	Non-severe ship damages
3	Severe	1 to 10 deaths	Severe damages
4	Catastrophic	>10 deaths	Total loss

Table 3.3. Risk matrix.

		Frequency						
		F1	F2	F3	F4	F5	F6	F7
S1	Minor	1	2	3	4	5	6	7
S2	Significant	2	3	4	5	6	7	8
S3	Severe	3	4	5	6	7	8	9
S4	Catastrophic	4	5	6	7	8	9	10

The above purpose is achieved by constructing and quantifying a diagram to display the distribution of risk, which is a typical cause-consequence model being a combination of FT and ET trees. The quantification is begun from the accident categories and then distributed down and up as deep as rationally. The available statistic data supported by judgement are used for this quantification.

The high risk areas are also addressed by ranking the risks using Frequency-Number (FN) diagrams or Potential Loss of Lives (PLL) values. The focus will be on them in next step. The best practice is to distinguish three levels of risk: Intolerable, ALARP and Negligible. The first level means that the risk cannot be justified except in extraordinary circumstances. The third level means that the risk is so small that no further precaution is necessary. The ALARP is situated between those two levels. The risk of shipping on a vessel should therefore be situated in ALARP range because sea travel can never be made so safe that the risk is Negligible [IMO, 2001a]. It is noted, that levels of risk for shipping are not quantified to date, though several propositions in this area have been elaborated [Skjong & Eknes, 2001] [Soares & Teixeira, 2001].

The purpose of step 3 is to propose effective and practical Risk Control Options (RCOs). Risk areas needed control are focused, potential Risk Control Measures (RCMs) are identified and then grouped into practical RCOs. The latter should address both existing risks and risks introduced by future technology, methods of operation and management.

The identification of RCMs is achieved by structured review techniques. These techniques include risk attributes and casual chains. The first ones relate to how the measure might control risk, and the second ones to where risk control can be introduced in the sequence of events leading from basic events to damages.

Works are continued in IMO under development of techniques to identify the various influencing factors to risk (connected with the environment, policy, organisation, etc.), named 'Regulatory Impact Diagram' [IMO, 2001b].

RCMs should be aimed at the following actions: (1) reducing the frequency of failures, (2) mitigating the effect of failures, (3) alleviating the circumstances of failures, (4) mitigating the consequences of accidents.

The RCMs are grouped into limited number of practical RCOs. When RCOs are assigned, the interested entities (stakeholders – person, organization, company, coastal state, flag state, etc.), which may be affected by the proposed measures, are identified.

The purpose of step 4 is to estimate and compare benefits and costs connected with the implementation of each RCO. Costs should be expressed in the terms of the life cycle costs of under analysis. Benefits may comprise reduction in fatalities, casualties, environmental damages and clean-up, indemnity of third party liabilities, etc., and increase in the average life of ships. Using various methods the evaluation of costs and benefits can be carried out.

The effectiveness of RCOs can be expressed by "Cost per Unit Risk Reduction (CURR)" and "Implied Costs of Averting a Fatality (ICAF)".

The purpose of step 5 is to define the recommendations for relevant decision-makers. The recommendations can be made in various kinds. The natural kind is the comparison and ranking of RCOs in the light of associated costs and benefits and identification of the most cost-effective RCO, which keep risk as low as reasonably practicable.

The results of FSA should be evaluated using risk evaluation criteria, but they are not set-ups up to now. In the Draft Guidelines [IMO, 2001b], it can be found that "It is desirable to determine risk evaluation criteria after wide and deep consideration for the use of the organisation and member government(s), which propose(s) new regulations or modification to existing regulations."

3.2.6 Discussion

The FSA methodology is particularly appropriate to the analysis of regulatory regime influencing the risk level of ships and searching safe solutions of them or their management. Safety is expressed by risk level connected with the life cycle of an analysed ship involving people, property and the environment. Also FSA fulfils the postulates of safety science: it treats safety as an attribute of man-technology-environment system and applies the probabilistic apparatus of safety quantification. Simultaneously FSA is adapted to analyses in the situations when historical data needed for safety modelling are lacking, and is completed by subjective judgements. However, FSA has some deficiencies.

Several problems have been identified with the use of the current method as proposed by the Maritime Coastguard Agency (MCA) to the IMO. These include:

1. Reliable data is usually not available for passenger vessels - and when it is available, there is a high level of uncertainty associated with the data.

2. The risk matrix approach is a simple subjective method to quantify the probability of occurrence of a hazard and severity of the associated consequences however it lacks a formal approach to quantifying expert judgement and opinion. Conflicting opinions of two different analysts on the severity of an accident could result in a deadlock.

3. It is usually 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 others.

3.3 Conclusion

In this chapter, several safety assessment methods and FSA have been reviewed in terms of their characteristics. Some typical fire safety models and evacuation models have been briefly studied. The review carried out in this chapter should provide basis for further research aimed at facilinating formal fire safety assessment of passenger ship.

The setbacks of the FSA methodology and typical safety analysis techniques discussed here are addressed by the development of various methods that are presented in the following chapters of this thesis.

References

ABS (2003), "Risk Evaluations for the Classification of Marine-Related Facilities", America Bureau of Shipping, June, USA.

Aldwinckle, D.S. & Pomeroy, R.V. (1983), "A Rational Assessment of Ship Reliability and Safety", RINA Transactions and Annual Report, pp 269-288, London, UK.

Andrews, J. D. & Moss, T. R. (2002), "Reliability and Risk Assessment", Longman Scientific & Technical.

Apostolakis, G. E., Guedes, S. C., Kondo, S. & Mancini, G. (1993), "Are Reliability and Risk Assessment Ready for Fuzzy Methods?", Reliability Engineering & System Safety, Vol 42.

Department of Energy (1992), "Cullen Report: The Public Inquiry into the Piper Alpha Disaster", ISBN 0 10 113102, London, UK.

Drager, H. K. & Orset, S. (1999), "EVAC – An Internet Software Program Solution for Evacuation Analysis of Passenger Vessels", Quasar Consultants, Oslo, Norway.

Galea, E. R., Owen, M. & Lawrence, P. J. (1996), "Computer Modelling of Human Behaviour in Aircraft Fire Accidents", Toxicology, Vol 115(1-3), pp 63-78.

Galea, E. R. (1999), "Principles and Practice of Evacuation Modelling", University of Greenwich, ISBN 1-899991-42-5, London, UK.

Garsmeur, P. L. & Anselme, G. D. (1998), "Simulating the Spread of Fire – the LUCIFER Software", INEC 1998 Surviving the War, IMarEST, London, UK, pp 133-138, 15-17 April.

Henley, E. J. & Kumamoto, H. (1996), "Probabilistic Risk Assessment and Management for Engineers and Scientists", IEEE Press, Second Edition, New York, USA.

House of Lords (1992), "Safety Aspects of Ship Design and Technology", Carver Report, Select Committee on Science and Technology, 2nd Report, HL Paper 30-I, February.

IMO (1997a), "Interim Guidelines for the Application of Formal Safety Assessment to the IMO Rule-Making Process", MSC/Circ.829. MEPC/Circ.335, London, UK.

IMO (1997b), "Formal Safety Assessment – Trial Application to High Speed Passenger Catamaran Vessels", MSC 68/Informal Paper, London, UK, 27 May.

IMO (2001a), "Formal Safety Assessment", Report of the Correspondence Group Part 1: Minutes of the Discussion, MSC 74/16, London, UK.

IMO (2001b), "Formal Safety Assessment". Report of the Correspondence Group Part 2: Draft Guidelines for FSA, MSC 74/16/1, London, UK.

Kobyliński, L. K. (1997), "Rational Approach to Safety Requirements", Proceedings of Marine Technology II Conference, Szczecin, Poland.

Lee, F. P. (1996), "Loss Prevention in the Process Industries", 2nd Edition, Butterworth-Heinemann, ISBN 0 7506 1547 8.

MIL–STD–882 (1969), "System Safety Program for Systems and Associated Subsystems and Equipment; Requirements", US Dept. of Defence, USA.

MIL-STD-1629A (1980), "Procedures for Performing a Failure Mode, Effects and Criticality Analysis", Military Standard, Naval Ship Engineering Centre, Washington DC, USA.

Owen, M. (1996), "The EXODUS Evacuation Model applied to Building Evacuation Scenarios", Journal of Fire Protection Engineers, Vol 8, No 2, pp 65-86.

Owen, M., Galea, E. R., Lawrence, P. J. & Fillippidis, L. (1998), "The Numerical Simulation of Aircraft Evacuation and Its Application to Aircraft Design and Certification", The Aeronautical Journal, Vol 102, No 1016, pp 301-312.

Peachey, J. H. (1995), "Formal Safety Assessment for International Shipping", Proceedings of Safety of Ships – Assessment and Regulation, Southampton, UK, 24-25 May.

Pillay, A. & Wang, J. (2003), "Technology and Safety of Marine Systems", Elsevier (Ocean Engineering Book Series), ISBN: 0080441483 Linacre House Jordan Hill, Oxford, UK.

SAFERELNET (2002), "Quantitative Risk Analysis – Report on Current Practice", Safety and Reliability of Industrial Products, Systems and Structures, September.

Sharp, G., Gwynne, S. & Galea, E. R. (2003), "The Effects of Ship Motion on the Evacuation Process", Subsection 3.1 - Critical Review on Model of Evacuation Analysis, Fire Safety Engineering Group, University of Greenwich, UK.

Sii, H. S. (2000), "Offshore Support Vessel Safety Assessment", PhD Thesis, School of Engineering & Advanced Technology, Staffordshire University, UK, September.

Sii, H. S., Wang, J. & Ruxton, T. (2002), "A Safety Based Decision Support System for the Design of Large Offshore Engineering Products", Final report submitted to the United Kingdom Health & Safety Executive for research contract *D3474*, UK.

Skjong, R., & Eknes, M. (2001), "Economic Activity and Societal Risk Acceptance", Proceedings of ESREL 2001 Conference, Torino, Italy.

Soares, G. C. & Teixeira, A. P. (2001), "Risk Assessment in Maritime Transportation" Reliability Engineering & System Safety, Vol 74.

Soma, D., Drager, K. H. & Bjørdal, P. (1995), "Computer Simulation for Optimisation of Offshore Platform Evacuation", OMAE 1995, Copenhagen, Denmark, June.

Spouse, J. (1997), "Risk Criteria for Use in Ship Safety Assessment", Proceeding of Marine Risk Assessment: A better Way to Manage Your Business, IMarEST, London, UK, 8-9 April.

Thompson, P. A. & Marchant, E. W. (1995a), "A Computer Model for the Evacuation of Large Building Populations", Fire Safety Journal, Vol 24, pp 131-148.

Thompson, P. A. & Marchant, E. W. (1995b), "Testing and Application of the Computer Model 'SIMULEX'", Fire Safety Journal, Vol 24, pp 149-166.

Thompson, P. A., Marchant, E. W. & Wu, J. (1996), "Modelling Evacuation in Multi-Storey Buildings with 'SIMULEX'", Fire Engineering Journal, Vol 56, No 185, pp 6-11.

Vassalos, D. (2001), Christiansen, G. & Kim, H., "Evi – Passenger Evacuation Performance Assessment in Ship Design and Operation", 8th TIEMS International Conference, Oslo, Norway.

Villemeur, A. (1992), "Reliability, Availability, Maintainability and Safety Assessment - Methods and Techniques", Vol 1, John Wiley & Sons, Chichester, UK.

Walter, W. J. & Richard, D. P. (1989), "Technical Reference Guide for FAST Version 18", Center for Fire Research, National Engineering Laboratory, NIST Technical Note 1262, USA, May.

Wang, J. (1994), "Formal Safety Analysis Methods and Their Application to the Design Process", PhD Thesis, Engineering Design Centre, University of Newcastle Upon Tyne, UK, July.

Wang J. & Kieran, O. (2000), "Offshore Safety Assessment and Safety Based Decision Making – the Current Status and Future Aspects", Journal of Offshore Mechanics and Arctic Engineering – Transactions of the ASME (American Society of Mechanical Engineers), Vol 122, No 2, pp 63-69.

Wang, J., Ruxton, T. & Labrie, C. R. (1995), "Design for Safety of Marine Engineering Systems with Multiple Failure State Variables", Reliability Engineering and System Safety, Vol 50, No 3, pp 271-284.

Wang, Z. F., Galea, E. R., Patel, M. K. & Ewer J. (2001), "Simulation One of the CIB W14 round Robin Test Cases Using the SMARTFIRE Fire Field Model", Fire Safety Journal, Vol 36, pp 661-677.

CHAPTER 4 – FIRE SAFETY ASSESSMENT ON PASSENGER SHIPS: APPLICATION TO AN ACCOMMODATION ZONE

Summary

This chapter provides an outlook on fire safety assessment, dealing with both its applicability to passenger ships and work needed to reach practical applications. A methodology is proposed for studying the fire scenarios in a typical ship cabin by using the currently available data including the specific fire load and the sprinkler performance (according to SOLAS: Safety Of Life At Sea). An example is demonstrated to show the basic assumptions, the models and the calculation procedures required to analyse a possible fire scenario in an accommodation zone of a passenger ship.

4.1 Introduction

Many of the greatest maritime tragedies have involved fire, especially fire onboard passenger ships. "The Morro Castle", "The Lakonia", "The Scandinavian Star" and "The Moby Prince" accidents are typical examples [Cowley, 1994]. Serious accidents at sea over the last few years indicate that more research work needs to be carried out on fire safety in ships.

Safety is the complement or antithesis of risk. Safety will be increased if the risk is reduced. There is no such thing as absolute safety. Some level of fire risk is virtually unavoidable. A passenger ship may be considered to be "very safe" from fire if a sufficiently "low fire risk" is associated with its structure, contents and occupants. The objective of fire safety assessment is therefore to reduce risk to life and property to acceptable levels to a property owner and society at large. This aim can be achieved by carrying out fire prevention activities, which would reduce the frequency of fires significantly and installing passive and active fire protection measures which would minimise the consequences if fire occurs [Ramachandran, 1999].

Fire safety on board passenger ships has come under scrutiny following a fire on board 'The Scandinavian Star' in 1990, which revealed a number of flaws in the International Maritime Organization (IMO) rules and regulations. This has led to the development of more comprehensive rules and regulations concerning fire safety of passenger ships [SNMA, 1996].

The new trend in the international regulations emphasizes the importance of the Quantitative Risk Assessment (QRA) as a design tool to comply with rules and to optimise specific solutions compatible with corporate strategies. In particular, it offers the possibility to better appreciate the benefits resulting from the combined effects of innovative solutions to a design problem [IMO, 1996]. QRA is a technique that can be used both qualitatively and quantitatively. It is used to understand and assess different hazards, and forms the basis of hazard management.

This chapter provides an overview on some of the typical techniques for fire risk assessment, with special emphasis on a framework for fire safety assessment to passenger ships.

4.2 Fire Safety Assessment

4.2.1 Goals of fire safety assessment

The main goals of fire safety assessment are:

1. To assess the fire risk by evaluating the frequency and possible consequences of each scenario.

2. To rank the risk against acceptability criteria, in order to highlight the areas needing risk reduction.

3. To compare different design solutions aimed at:
   - Preventing the fire occurrence.
   - Delaying fire growth and propagation.

- Minimising the consequences of fire.

4.2.2 Application

Historical data indicates that fires in accommodation areas can be regarded as events characterized by high specific impact on the people on a passenger ship, whose consequences range from mere discomfort to the potential for fatalities. This is also due to the absence of international maritime restriction on upholstered furniture and cloths currently used in passenger vessel's accommodations, unlike the properties of materials used for the boundaries of the spaces (bulkheads, floor and ceiling components and coverings) [Anderson, et al, 1993], subjected to fire restriction. Such reasons have suggested the possible occurrence of a fire event in a cabin of a passenger ship, constituting the initiating event for the analysis.

Investigations, available in literature, of fires on ships show that most injuries and fatalities are due to the effects of smoke and toxic fumes [Jenner, 1994, Jensen, 1994]. In this context, the present application is concentrated on the quantification of the severity degree of the various scenarios stemming from the initiating event. The severity is related to the impairment of the escape from a fire zone caused by smoke, on the basis of the time available to the passengers to leave the zone.

4.2.3 Methodology

A fire assessment framework is proposed to include the following steps:

1. Problem definition.

2. Construction of the Event Tree (ET).

3. Quantification of the outcomes.

4. Simulation of the consequences.

5. Risk evaluation.

They are detailed in the following:

1) The analysis is applied to a fire event in a cabin of a passenger ship. However, for its intended purpose, the analysis is intentionally restricted to a single piece of furniture burning in one cabin, allowing to screen the most critical scenarios. For this reason, the severity of the scenarios is viewed in relative terms; actually, in such conditions, the fire will self-terminate after some minutes. It is to be underlined that such limitations by no means affect the basic outline of the methodology; its application to broader scenarios only depends on the extent of the available information and resources employed.

2) The initiating event of the ET is the occurrence of the fire in a cabin, which is assigned a fictitious unitary frequency, as the absolute evaluation of fire risk is out of the scope of this analysis. The definition of the ET nodes, on the other hand, is set on the basis of the main factors affecting the fire escalation, namely:

   - Ignition (immediate/delayed depending on the effectiveness of preventive measures such as use of fire retarding materials).

   - Ventilation (mechanical and/or natural).

   - Correct operation of protective systems (effectiveness of control measures such as fire detection systems and of mitigation measures such as sprinkler systems).

   - Fire spread to adjoining compartments (e.g., due to openings, air conduits, etc.).

3) Once the ET is constructed, each node is assigned a probability of failure and success, obtained from databases or expert judgement. As the nodes in this case are independent, the probabilities of the ET outcomes occurring can be obtained [Angelo & Giovanni, 1997].

4) Each ET outcome scenario is to be assigned a severity level of possible consequences. In this case, this is carried out by means of a deterministic simulation through the fire zone model implemented in the FAST computer code [Peacock, et al, 2000]. In particular, the simulation of every scenario is conducted to yield results in terms of smoke interface height, temperature of upper layer and heat release rate, which are used to evaluate the consequences against the severity criteria.

5) Risk evaluation - Hazard screening.

Risk is concerned with the frequency (probability) coupled with the consequences (number of deaths, cost of damage to property or the environment) that might be caused.

Table 4.1. Generalised risk matrix table [IMO, 1999].

Risk matrix table		Frequency						
		Low ←→ High						
		F1	F2	F3	F4	F5	F6	F7
Minor	C1	1	2	3	4	5	6	7
Significant	C2	2	3	4	5	6	7	8
Severe	C3	3	4	5	6	7	8	9
Catastrophic	C4	4	5	6	7	8	9	10

Notes:
Each Ci (i = 1 to 4) stands for either the personnel safety (Si), environmental degradation (Ei) or business loss (Bi) consequence band.

Risk judgement can be based on a Probability-Consequence Interaction Table, which is known as risk matrix table (see Table 4.1). The purpose of the hazard screening is to provide a quick and simple way of ranking hazards, in terms of frequency and severity of possible outcomes with a view to setting priorities for more detailed risk evaluation. The risk matrix approach is a semi-quantitative risk ranking technique, which is used in the hazard screening process. For each appropriate combination, an assessment is made on the frequency (F) of the accident, and the severity of the consequences in terms of the personnel safety (S), loss in business (B) and environmental degradation or contamination (E).

In the risk matrix table, the magnitude of risk (defined as product of frequency and consequence) is measured on a scale of 1 to 10 as depicted in Table 4.1. This is called the Risk Ranking Number (RRN) which ranges from 1 (least frequent and least severe consequence) to 10 (most frequent and most severe consequence). Ranking of the various accidents determines their order in relation to one another. The RRN is indicative of the relative order of magnitude of risk [IMO, 1999]. In this chapter, the approach is used with reference to either historical data or expert judgements, and indeed, the FAST results.

4.3 Case Study

4.3.1 Problem definition

4.3.1.1 Fire hazard

In general, the fire hazard is related to the expected level of harm associated with the exposure to a fire or its effluent. In the context of this work, the fire hazard is associated with the loss of escape route.

An escape route is generally considered impassable when there are levels of temperature and smoke concentration, which are unacceptable for life safety ('Smoke' is used throughout this chapter to mean the total airborne effluent from the fire; it includes the gaseous aerosol and soot like products of fire) [USCG, 1995].

As a first step, only the height and temperature of upper layer were assumed to be representative of the escape route impairment, neglecting the smoke concentration. Within this assumption, this limited state approach adopted allows to associate probability values with the different escape time margins. Obviously this is not a measure of fatalities, which depends on the people's exposure to temperature and smoke toxicity [Angelo & Giovanni, 1997].

4.3.1.2 Limit criteria

The smoke level values corresponding to unacceptable toxicity and visibility reduction are different for each material and type of combustion process and many data are needed to set criteria. Without available data on the smoke released by furniture materials under the actual burning conditions (which affect the smoke mass concentration factor and thus the smoke optical density), a conservative approach was adopted, based on layer temperature and overall upper layer height from the floor, rather than on opacity [Angelo & Giovanni, 1997].

4.3.1.3 Layout and data

The SOLAS philosophy is aimed at confining any fire within a vertical zone. This analysis was applied to an area of a passenger ship compliant to 1997 Amendments of SOLAS [IMO, 1997].

The following are the basic available data and assumptions:

<u>Cabin description</u>

Passenger cabin's area is 15m^2(5m×3m), containing a trash can, an upholstered chair, a bed, a table and a toilet, and provided with low flame spread covering as per SOLAS II-2.Reg.34.3 [IMO, 1997].

Some information on the layout and fire load for a typical cabin was obtained from an internal investigation and from NFPA 72E [NFPA, 1987].

<u>Fire</u>

The data relative to the fire and necessary for the fire simulation are summarized in Table 4.2. They are relevant to the t-squared fire growth model and classified according to the BSI Standards, 1994 [BSI, 1994].

Table 4.2. Combustible items in the cabin.

Item	Fire Load (MJ/m^2)	Fire Growth Label	α (KW/S^2)	Peak Value (MW)	Virtual Time (S)	Source
Chair F-29	372	Fast	0.1055	2.11	70	NBSIR 83-2787, test 27
Bed	390	Medium	0.0086	0.66	90	NBSIR 83-2787, test 67
Wardrobe	504	Medium	0.0117	5.50	100	NBSIR 83-2787, test 42 [U S Department of Commerce, 1983]
Table	671	Medium	0.0257	1.75	64	Fire Data (2 Panel Workstation Test) [U S Department of Commerce, 1983]
Others	2890	Ultra-Fast	0.3300	2.50	-	Judgement
Total	**4827**					
Specific Fire Load	330 mJ/m^2					

The t-squared fire growth model can be represented with a power law relation of the following form:

$$Q \propto \alpha t^2$$

where Q is the heat release rate of the fire, α is the fire intensity coefficient, and t is time [Peacock, et al, 2000].

The items called "Others" encompass toilet, TV set, refrigerator, luggage and coverings. In order not to complicate the analysis too much, and since the simulation does not account for the behaviour of distributed fire load, these items were grouped in a single "dummy" object.

Ventilation

The cabin is equipped with a self-closing door as per the SOLAS regulations [IMO, 1997] and a window (with no restrictions about its constituting materials), depending on the cabin row.

The door is not airtight. Therefore, it was assigned a leakage even when closed.

The window is made of standard materials, and for this reason, it was assumed that it was unable to withstand the fire. This implies the window to be either open or broken, in those scenarios when it is present.

To take into account the natural ventilation (including leakage through the door), the following geometric characteristics of the openings were assumed:

- Door open: 0.6 m × 2.1 m,
- Door closed: 0.01 m × 2.1 m,
- Door grill: 0.2 m × 0.4 m, sill 0.2 m.

Mechanical ventilation supplies air into the cabins with a capacity of 277 kW, according to the technique of oxygen consumption calorimetry [SFPE, 1993].

Sprinkler

The sprinkler characteristics (temperature intervention and specific flow rate) are consistent to SOLAS [IMO, 1997].

The sprinkler has the following performances:

- Flow rate: 5 litre/m^2/min,
- Spray density: 8.3 $\times 10^{-5}$ m/s,
  It is the amount of water dispersed by a water spray-sprinkler. The units for spray density are length/time. These units are derived by dividing the volumetric rate of water flow by the area protected by the water spray.
- Activation temperature range from 68 °C to 79 °C.

Further, a Response Time Index (RTI) of 278 (m/s) $^{1/2}$ was assumed. The RTI quantifies how rapidly the detector links temperature rises in response to immersion in a hot ceiling jet.

Heat/smoke detectors

The cabin is equipped with an optical detector, whose actual response time should be evaluated by assuming its activation if the temperature increases by 30°C above the ambient temperature, Response Time Index (RTI) = 50 (m/s) ^{½} [IMO, 1997]; if the detection signal is not cleared within 120s, an alarm is activated in the affected zone.

Heat Release Rate (HRR) and fire growth

At first, the only presence of an upholstered chair was assumed to screen the most relevant and critical event sequences. This allows applying the HRR reference curve obtained by laboratory tests with the furniture cone calorimeter.

The models characteristic values are:

- Fire growth rate: α = 0.1055 kW/s^2, that is "fast" according to SFSE [SFPE, 1993] and between "fast" and "ultra-fast" according to the BSI Standards [IMO, 1997].
- Peak value: t = 140s, Q = 2.11 mW.
- Transition to decay at t = 160s.
- End combustion at t = 500s.
- Total heat developed = 372 mJ.

The fire growth model of the upholstered chair was derived from the reference test for the sprinkler performance verification as per IMO Resolution A800 (19) [Angelo & Giovanni, 1997]. The chair was assumed to be in a corner of the room.

4.3.2 Event Tree Analysis (ETA)

The initiating event frequency should be evaluated on the basis of the available historical data, adjusted appropriately if information relative to equipment, flammable inventory and ignition sources of the case is examined. In this analysis the initiating event frequency was not evaluated in order to emphasise the applicability of the methodology instead of an absolute measure of the fire risk.

In the present example, the fire escalation was deemed to be mainly conditioned by:

- Sprinkler performance.

- Ventilation effects.

The main assumptions are as follows:

- The outcomes of fire propagated to the whole fire load in the cabin (FRI : Full Room Involvement) were investigated only for the worst scenario.

- Only the natural ventilation was accounted for, due to the limited extent of the forced ventilation.

- The selected reference scenario is the fire of an upholstered chair in a cabin of a main vertical zone above the embarkation deck of a cruise ship; this constitutes the initiating event.

The ET was constructed on the basis of the above assumptions (see Figure 4.1). The ET nodes, in this example where only the natural ventilation is dealt with, are:

- Door status.
- Alarm activation.
- Sprinkler availability on demand.

The ET nodes probabilities are shown in Table 4.3 and the Event Tree Analysis (ETA) results are as shown in Table 4.4.

Table 4.3. ET nodes probability.

Event	Probability	Rationale
Door open	0.01	Engineering judgement: the door is self-closing type [Angelo & Giovanni, 1997]
Door closed	0.99	(1 - Door open)
Alarm activation	0.9	Expert judgement/historical data [Magnusson, et al, 1995]
Alarm failure	0.1	(1 - Alarm activation)
Sprinkler available	0.9	Expert judgement/historical data [Angelo & Giovanni, 1997]
Sprinkler unavailable	0.1	(1 – Sprinkler available)

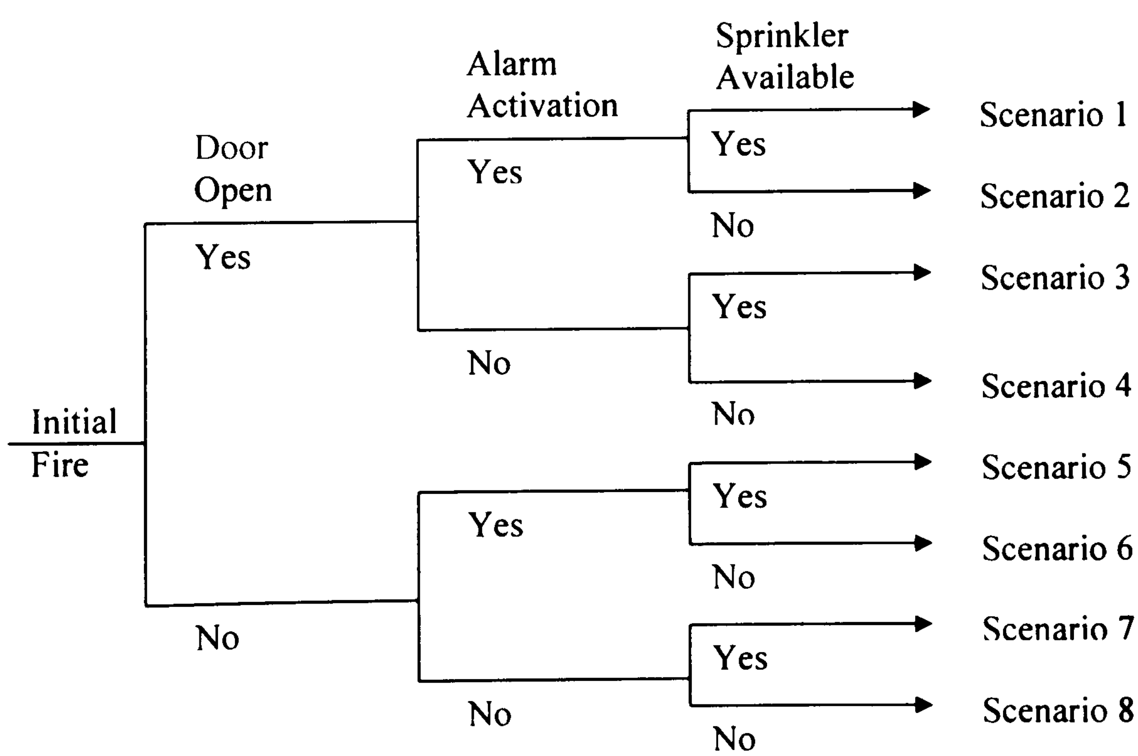


Figure 4.1. Event tree describing the eight scenarios.

Table 4.4. ETA results.

Scenario	Door	Alarm	Sprinkler	Probability
1	Open (0.01)	Success (0.9)	Success (0.9)	8.1×10^{-3} (0.01x0.9x0.9)
2	Open	Success	Failure	9.0×10^{-4}
3	Open	Failure	Success	9.0×10^{-4}
4	Open	Failure	Failure	1.0×10^{-4}
5	Closed	Success	Success	8.019×10^{-1}
6	Closed	Success	Failure	8.91×10^{-2}
7	Closed	Failure	Success	8.91×10^{-2}
8	Closed	Failure	Failure	9.9×10^{-3}

4.3.3 Quantification of the outcomes.

The evaluation of the consequences was accomplished by means of a physical simulation of the outcome scenarios 1 to 8, obtained using the FAST code (shown in Figures 4.2 to 4.9). The results of the simulation are displayed along with calculated values for temperatures, the height of the smoke layer and heat release rate. The graphs of heat release rate, upper layer temperature and layer depth can also be displayed by simulation. The FAST code was a zone model specifically developed for civil buildings [Richard, et al, 2000]. Therefore, it provides some cursory indications of the applicability to the shipping field.

4.3.3.1 Severity criteria

The criteria for estimating the severity of the consequences were thus defined as follows:

1. The Full Room Involvement (FRI) temperature was assumed to be 500 °C. By comparing this value to the corresponding temperatures of the 8 scenarios, considerations are made about the likelihood of FRI caused by the chair fire only.

2. The likelihood of the fire propagation in the nearby cabins only depends on the FRI occurrence; otherwise, the fire will self-terminate before the wall temperature gets high enough to cause the ignition of any object situated on the other side.

The main limitations of this study are listed in the following:

- The temperature results from the code are averaged; they can be accepted in this case where the space is small, but would be inadequate in large spaces.

- The 500 °C criterion corresponds to the flashover condition. In reality, it is also possible to reach FRI through propagation from the object to another within a room.

- The actual possibility of fire spread should take into account the actual walls' characteristics (resistance, thermal conductivity, etc.) and layout (e.g, existence of air gaps between the walls of two adjacent cabins that would delay the heat propagation, etc.).

- The danger of the smoke layer depends on more factors than the mere interface level, such as the optical density and the toxicity due to the presence of CO.

4.3.4 Simulation of the consequences

The simulation for the eight scenarios led to the following results (see the outcomes of scenarios 1 to 8 shown in Figures 4.2 – 4.9):

1. In those scenarios where the door is open (1, 2, 3 and 4) the fire is fuel-controlled (that is, its growth is limited by the amount of the fire load).

2. <u>With sprinkler operating correctly (scenarios 1, 3, 5 and 7)</u>

The sprinkler is instrumental in reducing the fire heat release rate, and consequently the possibility of FRI; as to the smoke layer, the consequences worsen according to the air ingress (1 and 3 being more severe than 5 and 7).

With sprinkler unavailable (2, 4, 6 and 8)

The fire heat release rate increases, and consequently the possibility of FRI, increases; as to the smoke layer, in this case, scenarios 2 and 4 are more severe than 6 and 8.

3. In those scenarios where the door is closed (5, 6, 7 and 8) the fire is ventilation-controlled (that is, its growth is limited by the amount of oxygen). Due to the limitations in the combustion the smoke produced depends on the time length of the fire.

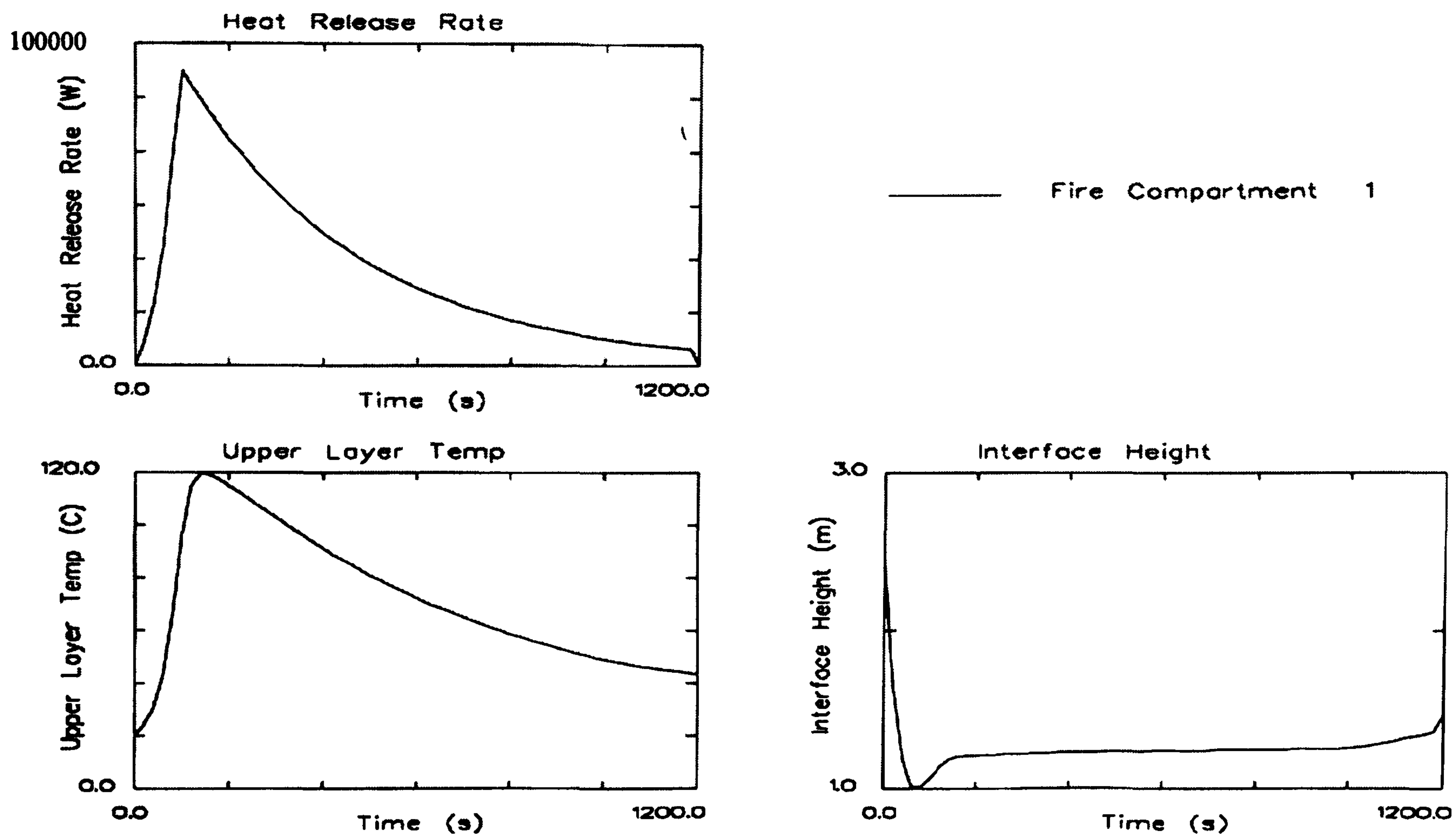
4.3.5 Risk evaluation - Risk Matrix Approach

According to the probability and to the simulation results, the overall ranking of the eight scenarios is produced as follows:

Table 4.5 gives the interpretation of the frequencies F1 to F7.

Table 4.5. Key to the frequency bands for risk table.

Frequency	Probability
F1	0.0000 – 0.0001
F2	0.0002 – 0.0010
F3	0.0011 – 0.0090
F4	0.0091 – 0.0100
F5	0.0101 – 0.0900
F6	0.0901 – 0.8020
F7	0.8021 – 1.0000



Outcome of Scenario1.

Figure 4.2. FAST result of scenario 1.

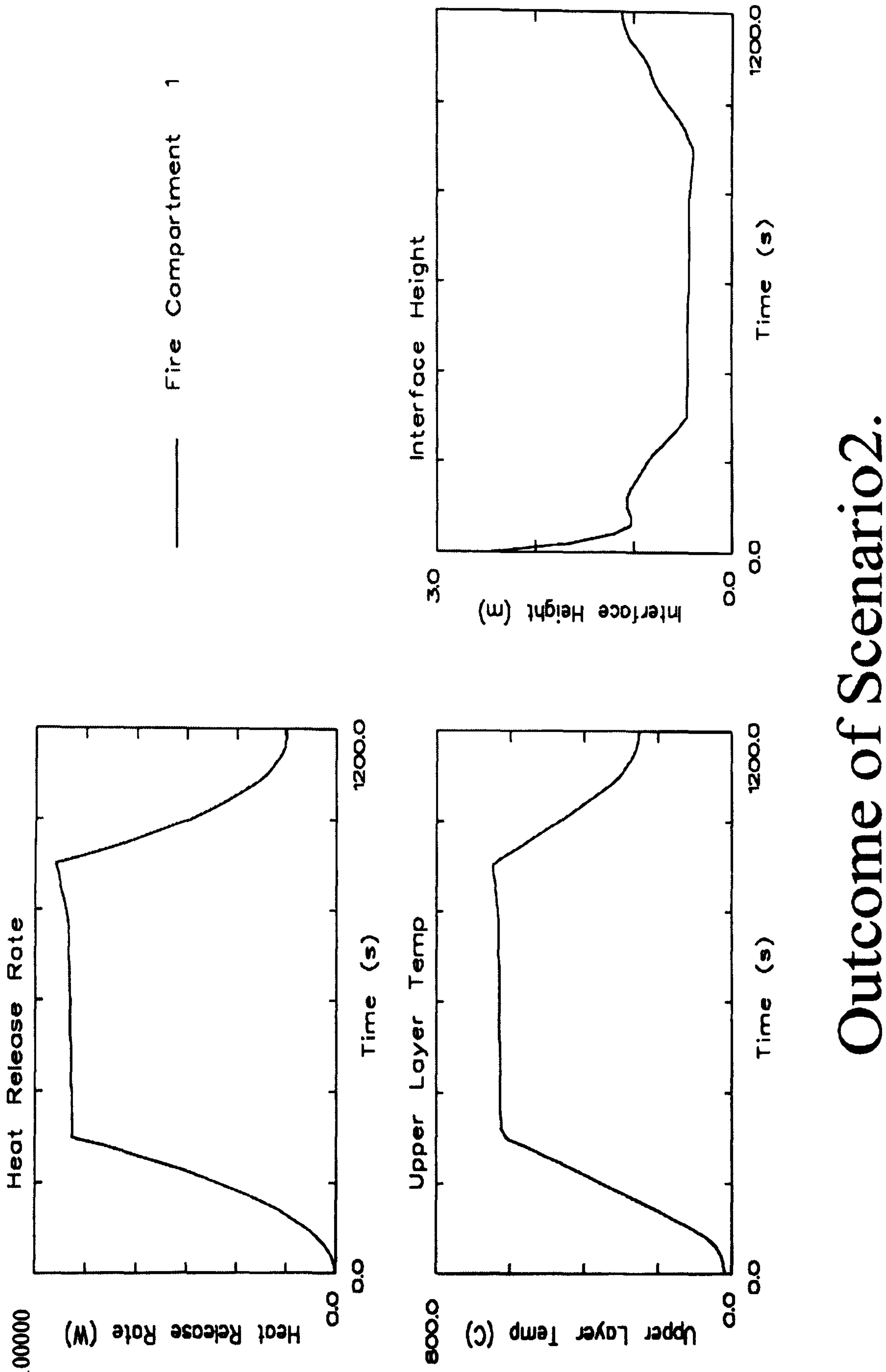


Figure 4.3. FAST result of scenario 2.

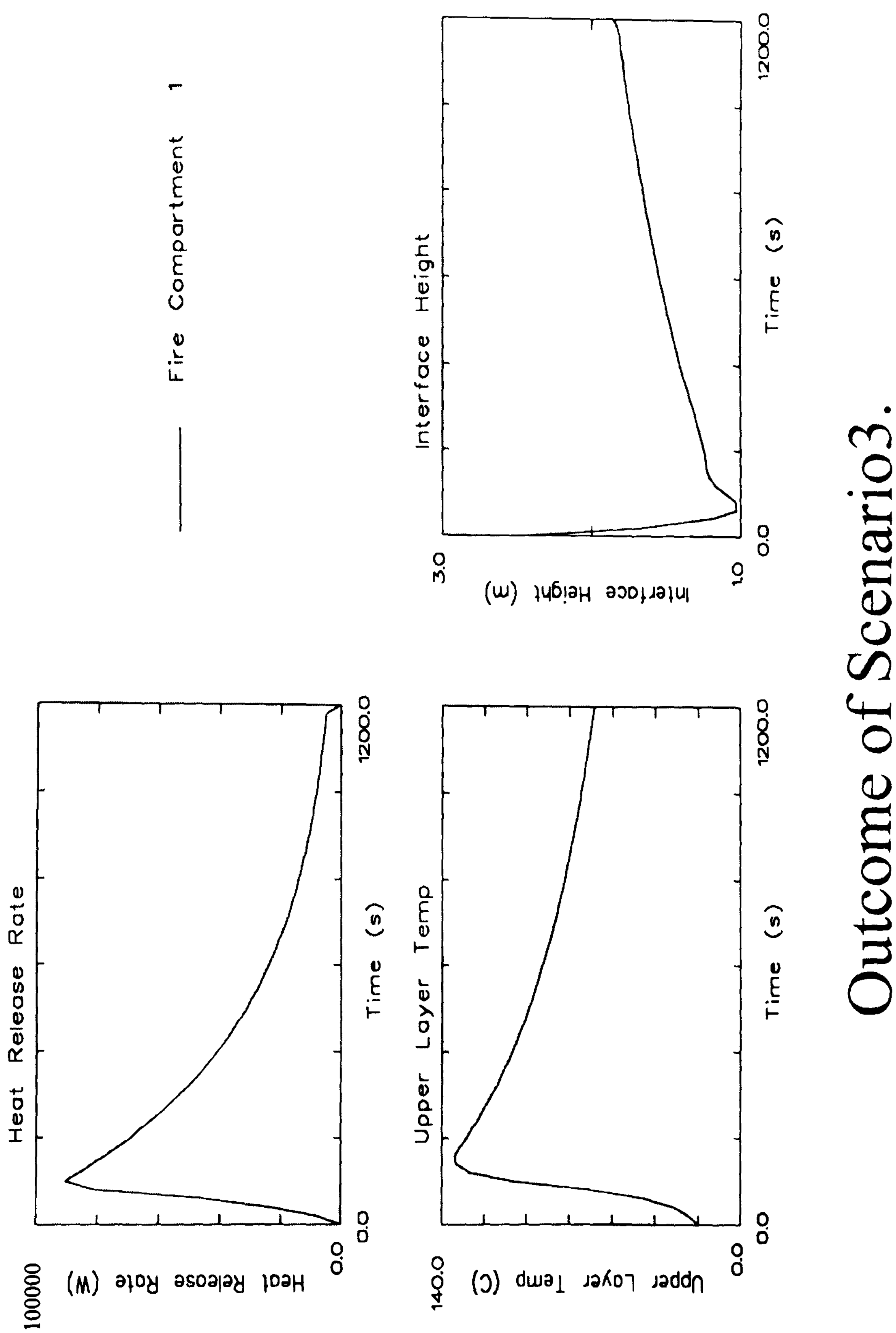


Figure 4.4. FAST result of scenario 3.

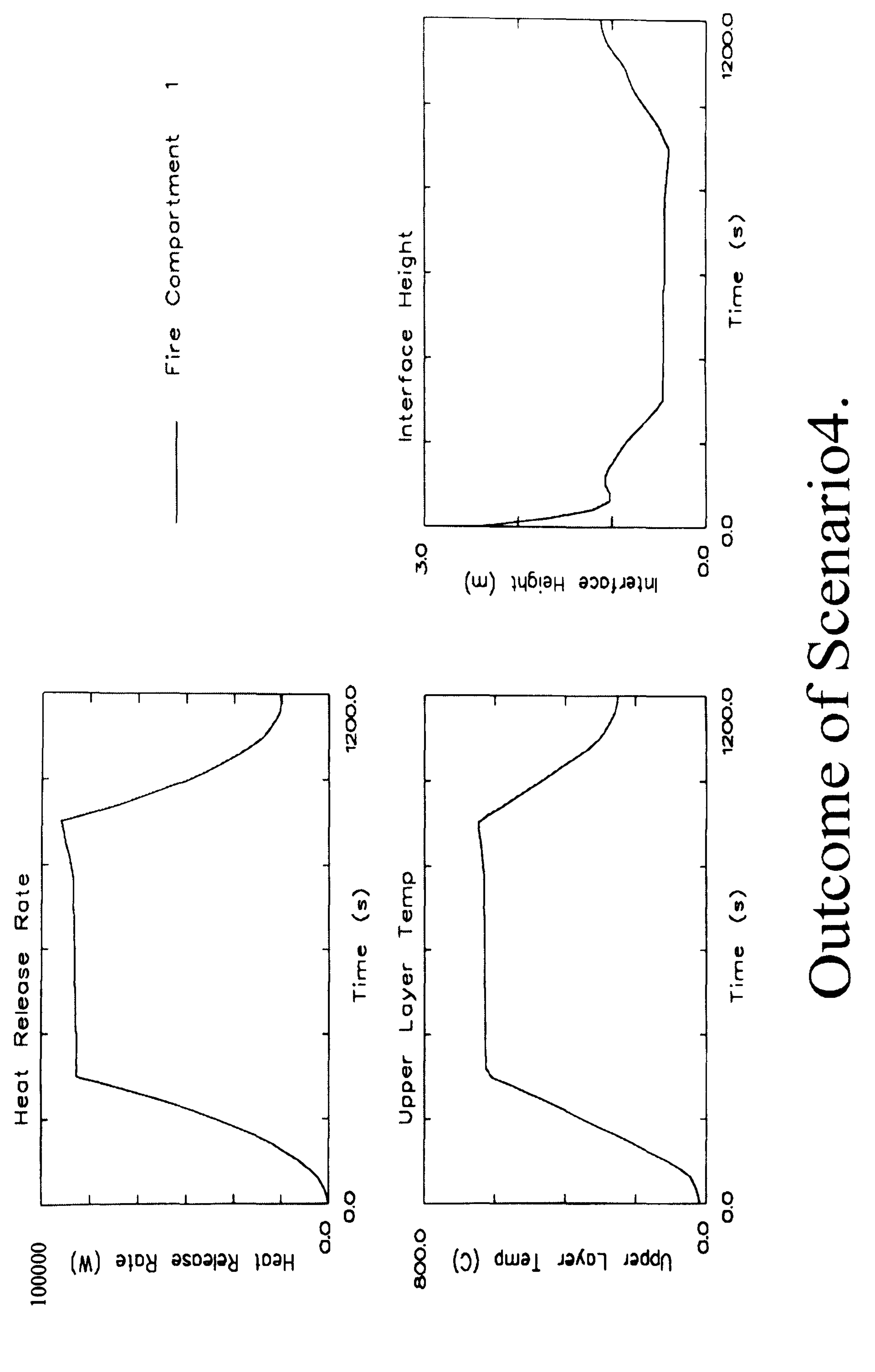


Figure 4.5. FAST result of scenario 4.

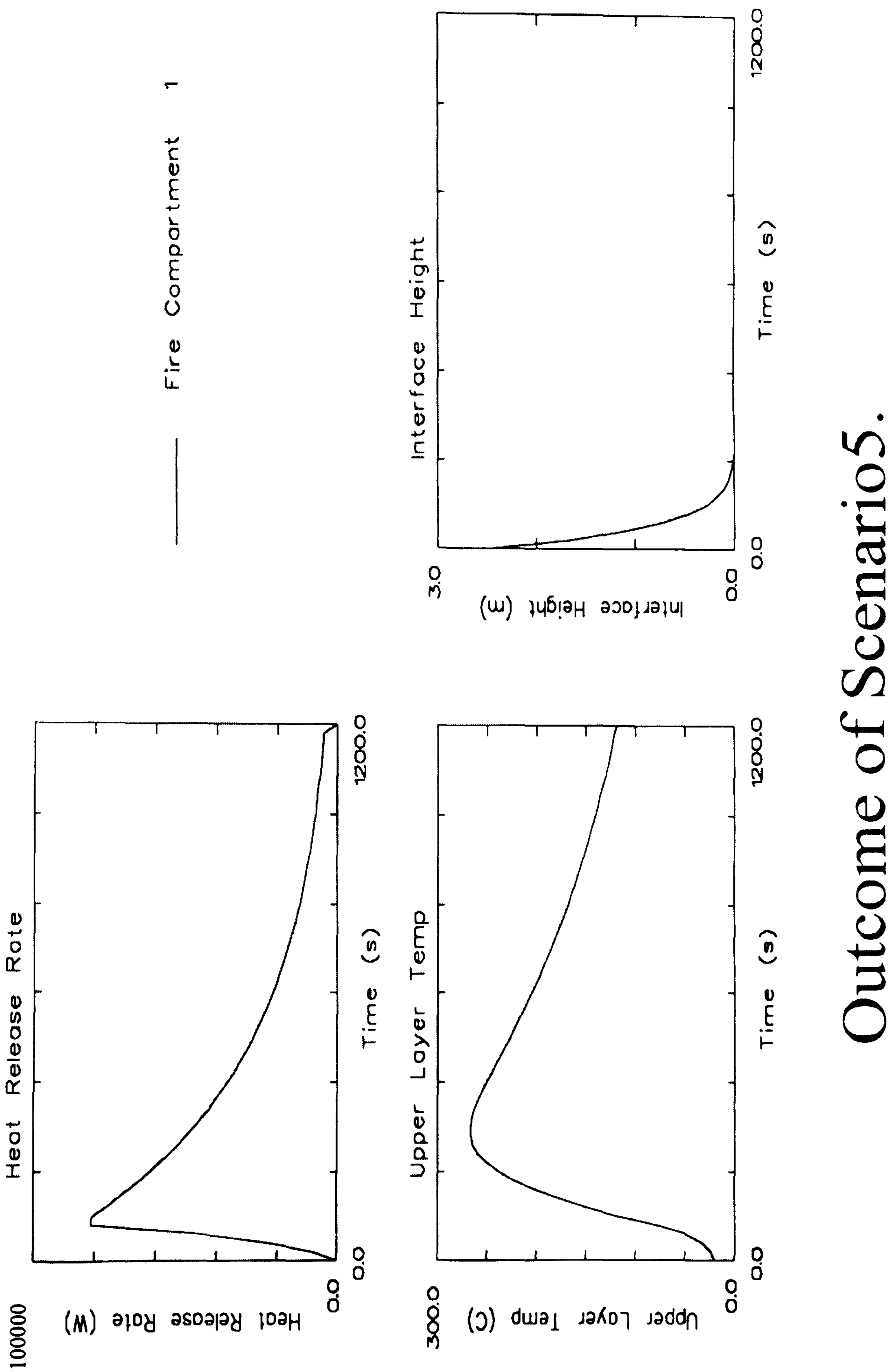


Figure 4.6. FAST result of scenario 5.

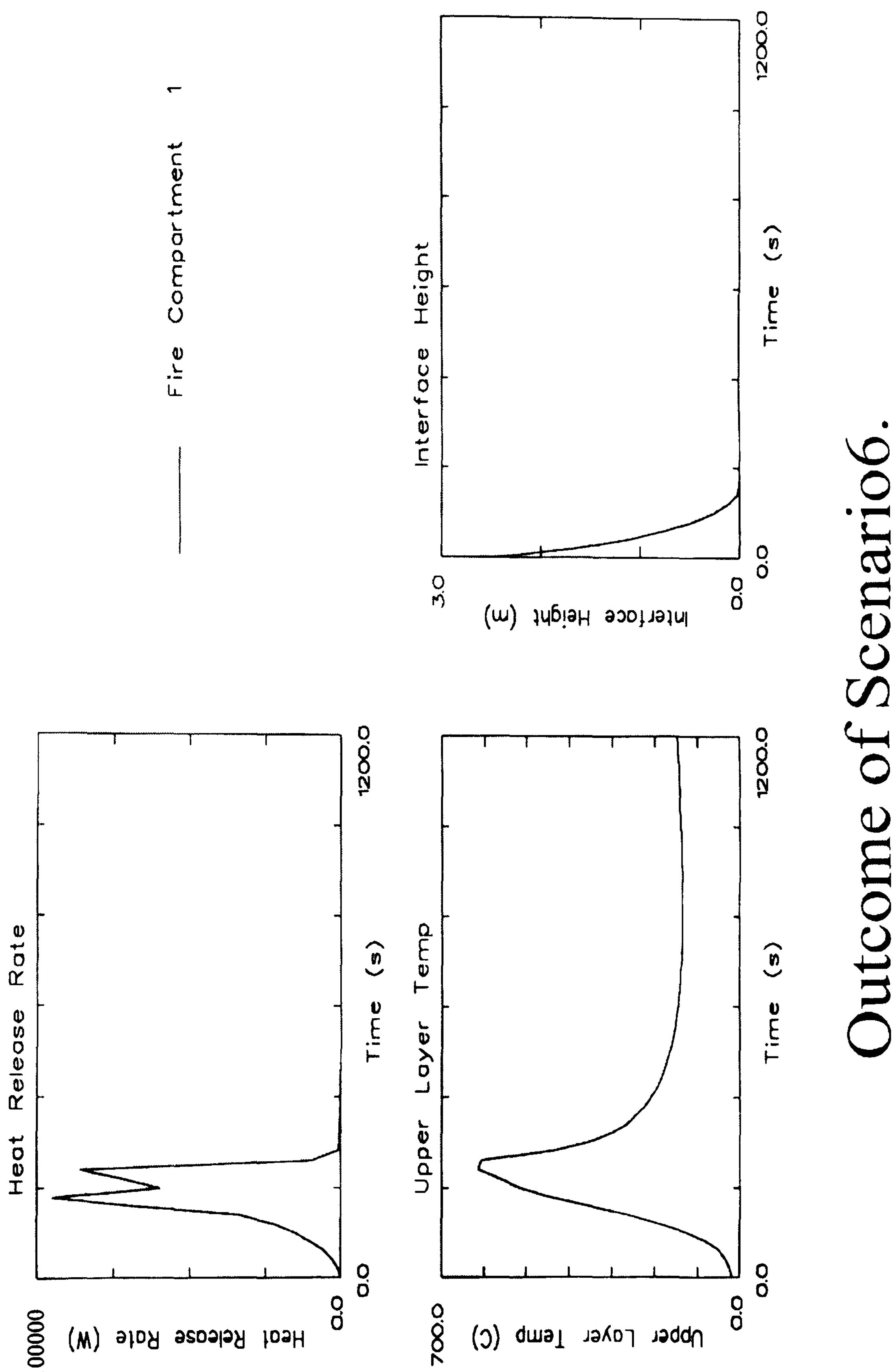


Figure 4.7. FAST result of scenario 6.

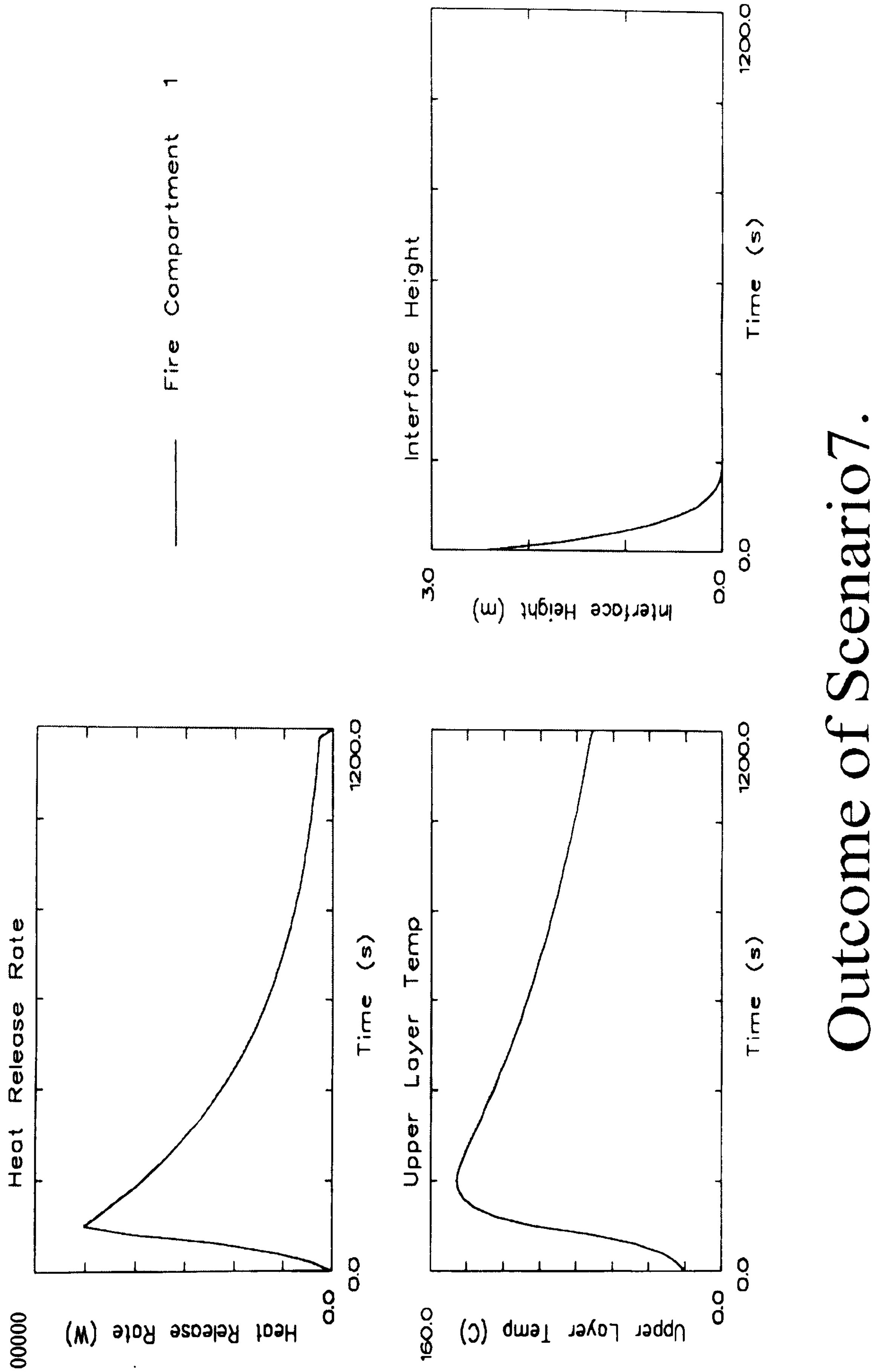


Figure 4.8. FAST result of scenario 7.

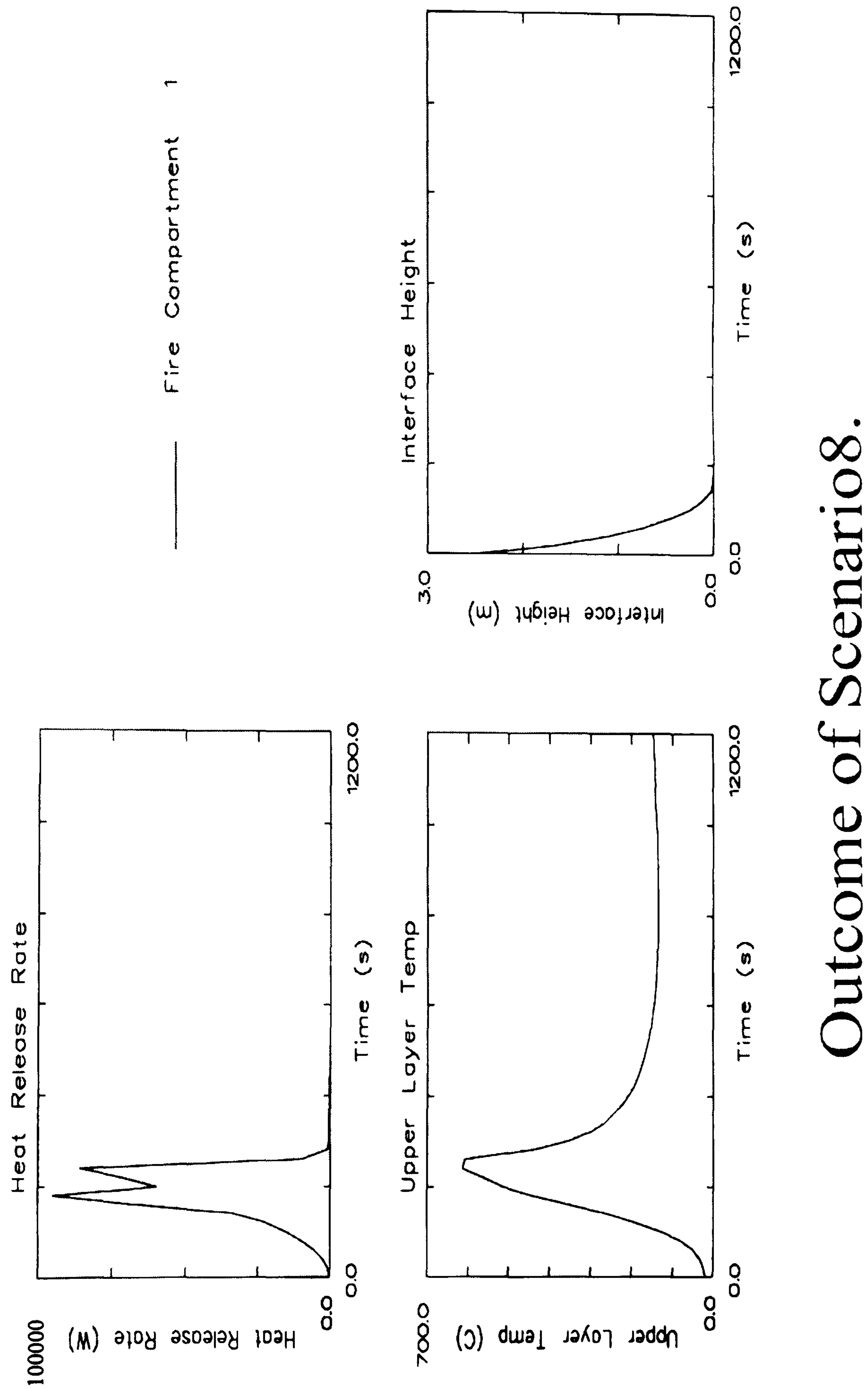


Figure 4.9. FAST result of scenario 8.

Table 4.6 shows the key to the consequence bands for Heat Release Rate (HRR), Upper Layer Temperature and Interface Height.

Table 4.6. Key to the consequence bands for risk table.

C1	Minor	Single or minor injuries
C2	Significant	Multiple injuries
C3	Severe	Single death
C4	Catastrophic	Large number of deaths

Table 4.7 represents a fire accident in the cabin. This table is generated by analysing the data in terms of its occurrence and severity of consequences from the FAST results shown in Figures 4.2 – 4.9.

For example,
Scenario 1 – Heat Release Rate:
Frequency band = F3 (Table 4.5)
Consequence band = C1 (Table 4.6 and expert judgement with FAST results)
Risk Matrix Scale = 3 (Table 4.1)

The judgement of frequency bands is based on the results obtained from Table 4.4. The consequence bands (i.e., C1-C4) are assessed by expert judgement with reference made based on the results obtained from simulation for each scenario.

Table 4.7. Fire ranking using risk matrix approach.

	Heat Release Rate (HRR)	Upper layer temperature	Interface height
Scenario1	F3 C1 = 3	F3 C2 = 4	F3 C1 = 3
Scenario2	F2 C2 = 3	F2 C4 = 5	F2 C2 = 3
Scenario3	F2 C1 = 2	F2 C3 = 4	F2 C2 = 3
Scenario4	F1 C2 = 2	F1 C4 = 4	F1 C2 = 2
Scenario5	F6 C1 = 6	F6 C2 = 7	F6 C1 = 6
Scenario6	F5 C3 = 7	F5 C3 = 7	F5 C1 = 5

Scenario7	F5 C1 = 5	F5 C2 = 6	F5 C1 = 5
Scenario8	F4 C3 = 6	F4 C3 = 6	F4 C1 = 4

Table 4.7 was then produced which gives a ranking number for each accident category. Following the tabulation of this data, the 'equivalent total' of risk ranking number can be derived as shown below. This is an approximate calculation based on the individual risk ranking values for all the scenarios. 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). This will enable the process of ranking each scenario according to its influence on the safety of the cabin. The high-risk areas are then distinguished and attention is drawn to them.

Based on the information obtained in Table 4.7, the ranking order is produced as follows:

	Heat Release Rate	Upper layer temperature	Interface height	Total (same weight)
Worst	6	5 & 6	5	5 & 6
scenario	5 & 8	7 & 8	6 & 7	7 & 8
↑	7	2	8	2
↓	1 & 2	1, 3 & 4	1, 2 & 3	1
Best	3 & 4		4	3
scenario				4

Calculation of 'Equivalent Total' for the Fire Accident in the Cabin:

The number of occurrences in the Risk Table of a risk ranking score of 4 is 4; a risk ranking score of 5 is 4; a risk ranking score of 6 is 5; a risk ranking score of 7 is 3; risk ranking scores of 3 and below have been ignored as not significant.

Using 7 as a base then: 'Equivalent Total' = 7 + log (3.544) = 7.55

Alternatively using the risk ranking score of 4 as the base, then: 'Equivalent Total' = 4 + log (3544) = 7.55.

If there are several cabin design options available, the above procedure can be applied to each of them to obtain the risk ranking score. The design option with the lowest risk score may be chosen. If design criteria such as costs are considered in the design process, the obtained risk scores can be combined with other design criteria to make decisions.

4.4. Conclusion

The analysis has basically highlighted the following points:

1. From a simulation viewpoint, the fire growth model is of paramount importance to really simulate different options in the ship materials and the sprinkler intervention; the fire load basically gives indications of the heat energy stored, thus of the likelihood of FRI and fire spread.

2. In such constrained fires, the HRR is driven by the ventilation, which tends to smooth down the peak values as obtained by the tests in fuel-controlled conditions; on the other hand, the unburned paralysed fuel could be transported with the smoke into other compartments, thus contributing to propagate the fire. The assumption of free ventilation that would control the fire can be misleading, as it could make the situation worse.

3. The test case demonstrates that sprinkler intervention and performance is a key factor to increase the time available to evacuate without hazard for the people.

Generally speaking, the application of this methodology is demanding in terms of specific fire data of the involved materials and robust simulation models and tools. However, the performance based rules, which are being promoted by the new trends in regulations, should necessarily also be based on risk estimations; these, in turn, will be typically developed on models and parameters characterised by uncertainty and described by statistical distributions.

In this analysis, many data not available at hand were evaluated by engineering judgement. However, as fire safety engineering technology grows and matures, the availability of data will increase, making this methodology an effective and useful tool to focus on the most effective solutions among different designs.

References

Anderson, P., Robertsson, H. & Wikman, J. (1993), "A Fire Safety Survey of Materials Used in Passenger Vessels", Accommodations, Research Report MariTerm AB, ISBN 91 630 1809N, Goteborg, Sweden, 8 April.

Angelo, T. & Giovanni, G. (1997), "Fire Risk Analysis on Cruise Ships – Application to an Accommodation Zone", Paper 3, Fire at Sea, RINA, London, UK, 20-21 November.

BSI (1994), "The Application of Fire Safety Engineering Principles to Fire Safety in Buildings", British Standards Institute Standards 94/340340 DC (draft), UK.

Cowley, J. (1994), "Fire Casualties and Their Regulatory Repercussions", Paper 1, IMAS 94, Fire Safety on Ships, Developments into 21st Century, London, UK, 26-27 May.

IMO (1996), "Formal Safety Assessment – Draft Guidelines for FSA Application to the IMO Rule-making Process", IMO Maritime Safety Committee, MSC 68/14, London, UK, 18 December.

IMO (1997), "SOLAS, Consolidated Edition", London, UK.

IMO (1999), "Formal Safety Assessment – Trial Application to High Speed Passenger Vessels", IMO Maritime Safety Committee, MSC 68/Informal Paper, London, UK, 27 May.

Jenner, B. P. (1994), "Technical and Human Factors in the Prevention and Control of Shipboard Fires", Paper 2, IMAS 94, Fire Safety on Ships, Developments into 21st Century, London, UK, 26-27 May.

Jensen, K. H. (1994), "Smoke Control in Cruise and Passenger Vessels", Paper 13, IMAS 94, Fire Safety on Ships, Developments into 21st Century, London, UK, 26-27 May.

Magnusson, S. E., Frantzich, H. & Harada, K. (1995), "Fire Safety Design Based on Calculations, Uncertainty Analysis and Safety Verification", Lund University, Institute of Technology, Department of Fire Safety Engineering, Report 3078, Sweden.

NFPA (1987), "National Fire Protection Association 72E – Standard on Automatic Fire Detectors", USA.

Peacock, D. R., Reneke, A. P., Jones, W. W., Bukowski, W. R. & Forney, P. G. (2000), "A User's Guide for FAST: Engineering Tools for Estimating Fire Growth and Smoke Transport", NIST (National Institute of Standards and Technology), Special Publication 921, USA.

Ramachandran, G. (1999), "Fire Safety Management and Risk Assessment", Facilities, Vol 17, No 9/10, pp 363-376.

SFPE (1993), "The SFPE Handbook of Fire Protection Engineering", Society of Fire Protection Engineers, National Fire Protection Association, USA.

SNMA (1996), "FSA: Introduction of Modern Risk Assessment into Shipping", Swedish National Maritime Administration, Sweden, 2 August.

USCG (1995), "Department of Transportation – Report of the Cruise Ship Safety Review Task Force", United States Coast Guard, USA, 31 October.

US Department of Commerce (1983), National Bureau of Standard, National Engineering Laboratory, "Fire Performance of Furnishings as Measured in the NBS Furniture Calorimeter. Part 1", NBSIR 83-2787, USA.

CHAPTER 5 – DEVELOPMENTS IN SMOKE CONTROL SYSTEM FOR PASSENGER SHIPS: APPLICATION TO AN ACCOMMODATION ZONE

Summary

One of the most important means to avoid catastrophes in case of fire onboard passenger ships is to ensure that the passengers can escape in a quick and safe manner. One of several precautions to take is to try to control the spread of the smoke in a simple and reliable way. In this way the area where people are in contact with the smoke can be minimised and better visibility to escape from the smoke can be secured.

5.1 Introduction

Fires onboard a number of passenger ships including the 'Scandinavian Star', have caused the International Maritime Organization (IMO) to tighten up the requirements for fire safety. Therefore it has been decided that in the future it will be a requirement that sprinklers and smoke detectors are installed in all the accommodation areas of passenger ships [IMO, 1997].

A Danish investigation shows that approximately 90% of the persons killed in shipboard fires have perished due to smoke exposure and only 10% due to heat exposure. The disasters on board Scandinavian Star, M/S TOR Scandinavian and other passenger ships, have further demonstrated that smoke could spread very quickly inside the ships [Anderson, et al., 1993].

Although shutting down the Heating, Ventilating and Air Conditioning (HVAC) systems prevents fans from forcing smoke flow and stops supply of oxygen, it does not prevent smoke movement due to smoke buoyancy, stack effect, expansion or draught due to the wind. Therefore, it is not sufficient only to detect the toxic smoke. Safety will be increased further if the spread of smoke inside the ship is also reduced.

In order to achieve this, additional requirements are needed, that is, automatic release of fire doors into closed position and activation of the smoke control system when smoke is detected [Abell, 1999].

Previous studies have shown that fire is extremely difficult to locate in cabin areas [Jensen, 1994]. Fires in public spaces are often easier to locate and thus can be extinguished more quickly. Further, evacuation of passengers from public spaces is not as difficult as from cabin areas, where people may be sleeping. Therefore, smoke control in cabin areas is emphasised in this chapter.

5.2 Background

5.2.1 Regulations

The fire aboard "Scandinavian Star" on passage between Oslo and Frederikshavn on 7 April 1990 prompted the IMO Fire Prevention (FP) sub-committee at FP37, 1992 to establish the philosophy on smoke control and ventilation for eventual inclusion into the revised version of Chapter II-2 SOLAS (Safety Of Life At Sea) 1974.

All passenger ships built after 1 January 1994, which have an atrium spanning three or more decks and containing combustibles such as furniture, shops, offices, restaurants etc. shall be equipped with a smoke extraction system. It shall be activated by the smoke detection system automatically or manually such that the entire volume within the space can be exhausted in 10 minutes or less, SOLAS Chapter II-2 Regulation 32 (Ventilation Systems) 1.7.

5.2.2 Definition of smoke

Smoke is identified as a key factor and smoke control has to be dealt with carefully [Chow, 1995, 1997]. Sudden horrific explosions can maim, burn and subsequently kill people but the insidious development of smoke containing its cocktail of deadly poisonous gases invariably kills more [Graham, 1995].

The chemical reaction known as polymerisation begins with a monomer, perhaps the most common of which is ethylene. Any substance that contains carbon can give off:

1. Carbon monoxide (CO), a narcotic gas, which is lethal. It is produced, in copious amounts, as a result of incomplete combustion of materials containing carbon and is present in most fires.
2. Carbon dioxide (CO_2), another highly poisonous gas, which is also produced in large quantities. Inhalation stimulates respiration and this, in turn, increases inhalation rates of both oxygen and possible toxic gases and vapours produced by the fire.

If chlorine is added, the resultant molecule becomes PVC, polyvinyl chloride that is used to make a vast array of products such as adhesives, anticorrosion sealants, blister packages, bottles, electrical insulation, etc. Hydrogen chloride is evolved when these substances burn [Fe & Hadjisophocleous, 2000].

High levels of prussic acid and hydrogen cyanide, which are given off when nylon, wool or polyurethane burns, were found in the fatalities of the Scandinavian Star. This led to immediate investigation into the content of laminates found aboard various vessels. The mixture of these added gases increases the speed of the toxicity [Abell, 1999].

The way in which any substance burns depends on many parameters and conditions, some of which may include:

- Its shape and size.
- The source of ignition.
- The amount of oxygen needed.
- The rate of flame spread.
- Ventilation and other environmental conditions.

However, it is certain that, lack of visibility and disablement by toxic gases in smoke often impedes the escape of occupants [Abell, 1999].

5.2.3 Smoke movement

Smoke spread has been a main interest of fire science and engineering [He & Beck, 1997]. The phenomenon of smoke spread, as an important factor in life safety design, must be understood and estimated [Kim, et al., 1998].

There are two main factors, which determine the movement of smoke and hot gases from a fire. These are:

1. The buoyancy (or mobility) of the smoke due to pressure differentials developed by:

   a. Expansion of the gases heated by the fire.

   b. Difference in density between the hot gases above the flames and the cooler air, which is surrounding the fire.

2. The normal air movement inside the ship caused by:

   a. The stack effect: the pressure differential due to the temperature of the air inside a room being at a different temperature from the air outside the room.

   b. The wind pressure effect, due to penetration through leakages.

   c. The mechanical air handing systems.

The smoke control system must be designed in such a way that it is not overpowered by the forces mentioned above [Abell, 1999].

5.2.4 Main criteria for design of smoke control system

It is emphasised that only smoke control systems in the cabin areas and adjacent stairways will be discussed in this chapter. There are a number of criteria, which are of great importance for the design of a smoke control system. Among these criteria are:

1. The system shall be designed to handle fire.
2. The fire doors close automatically when a fire is detected.
3. Entry of smoke into the areas adjacent to the burning area, such as a stairwell and the other cabins, must be prevented.
4. Differences in pressure must not be so great that door opening forces will become too excessive.
5. The smoke control system should be activated as required.

Further, as far as economy and space are concerned it is aimed at utilising the traditional HVAC systems to the greatest possible extent [Jensen, 1994].

5.2.5 HVAC (Heating Ventilating and Air Conditioning) system for cabin areas

Normally supply air for the cabins is distributed from the air handling unit in a high-velocity, tubular, dual duct system. The air coming from the two pipes is mixed in an air terminal device, often known as a cabin unit, which is normally located in the ceiling. By means of a coupled two-valve system controlled by a thermostat, the air coming from the two pipes can be mixed in such proportions that the temperature required by the passenger can be obtained. The air enters the room through a diffuser fastened to the air terminal device. Both constant air volume systems and variable air volume systems are used (see Figure 5.1).

Normally there is a smaller positive pressure in the cabin in order to prevent contaminated air from entering the air-conditioned cabin. Discharge of air normally takes place partly through bathroom and partly to corridor. Typically 30-40% of the air is exhausted through the exhaust valve mounted in the bathroom. The air enters the bathroom through a slot under the door into the bathroom. The rest of the air passes through a grille in door/under door/through duct under bathroom into the corridor. Usually there are several air terminal units for exhaust in the corridor. This means that normally there is negative pressure in the corridor and the bathroom.

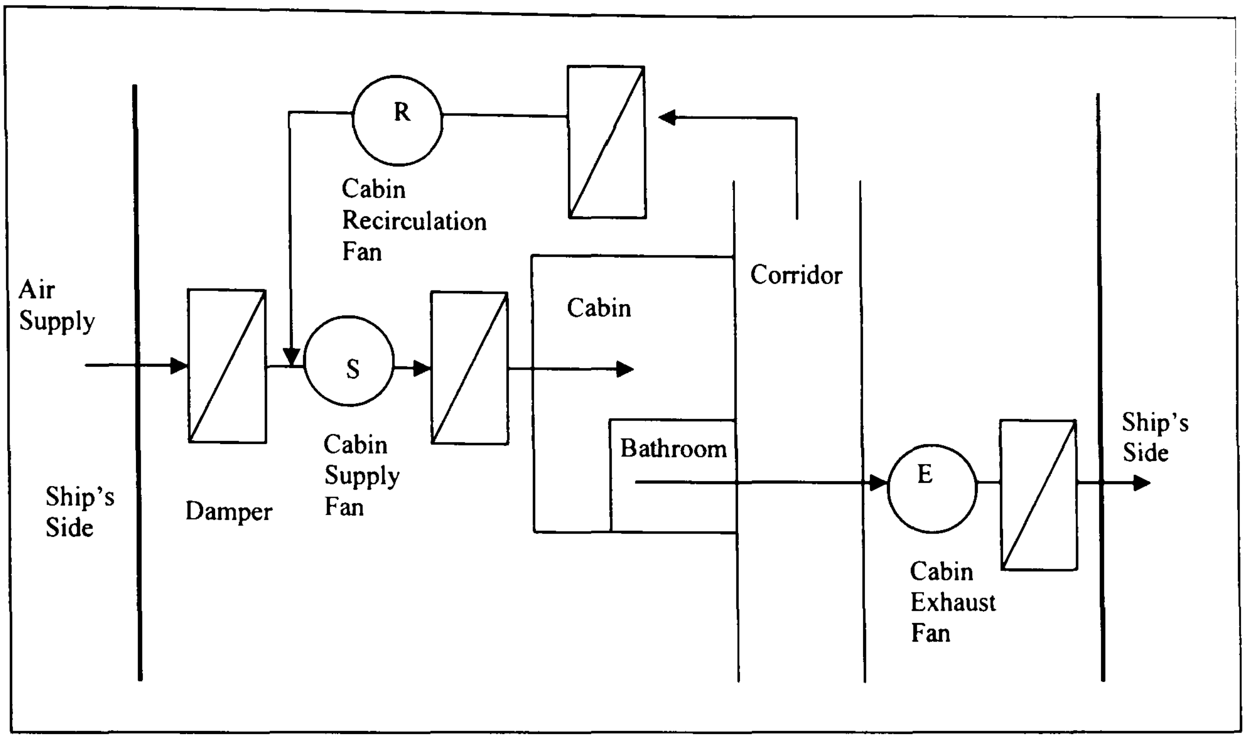


Figure 5.1. HVAC system for cabin areas (energy recovery by recirculation).

There are two ways of designing the exhaust air system. The choice depends on the energy recovery method. When a rotary enthalpy exchanger is chosen, usually all exhaust air is exhausted through one exhaust fan. Energy recovery by using recirculation of air is another method. In this case two separate exhaust systems are necessary. Exhaust air from bathrooms is not used for recirculation [Jensen, 1994].

5.2.6 HVAC (Heating Ventilating and Air Conditioning) system for stairways

Halls and major stairwells are normally served by an air-handling unit, which does not serve any other spaces in the ship. The air supplied is distributed from the air-handling unit in a rectangular, single-duct system. The air enters the stairwell through diffusers. Usually the air volume exhausted from the halls and stairwells is equal to the air volume supplied – a balanced system (see Figure 5.2).

5.2.7 Fire in cabin

In case of fire in a cabin the optimal smoke control system would ensure that the smoke is extracted by means of smoke extraction in the cabin. Smoke entering into the corridor would be avoided by prohibiting surplus air from the cabin from entering into the corridor.

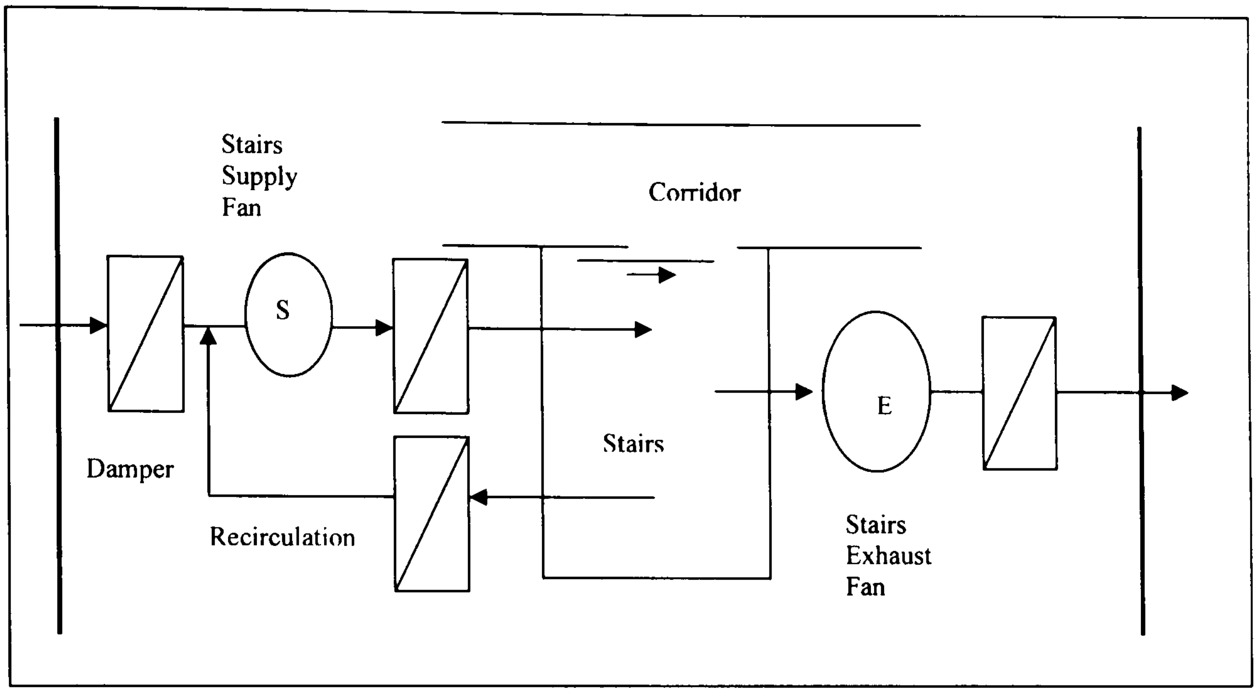


Figure 5.2. HVAC system for a stairs (energy recovery by recirculation).

Large positive or negative pressures in the area consisting of the cabin and the bathroom must be avoided. Therefore, the mass flow of air exhausted by the exhaust system must be equal to the mass flow of air supplied by the air supply system.

This solution would require quite a complex and expensive HVAC system, especially when a variable air volume system is used. Further, it is almost impossible for a system traditionally built to extract additional air/smoke through the exhaust valve in the bathroom, even by means of a bigger fan. This is primarily due to strict space limitations and thus to limitations of the pipe sizes [Jensen, 1994].

5.2.8 Fire in stairway

In case of fire in the stairway the removal of smoke can take place through a mechanical smoke extraction fan located at the top of the stairway. In order to prevent smoke spread into the lower decks the exhaust duct system used during normal HVAC operation in the stairway has to be shut off.

As in all smoke control systems replacement air must be allowed to enter the space. In order to ensure an effective extraction arrangement the replacement air has to enter the stairway through numerous openings at low levels. The inlets could be connected to ducts leading directly to open air [Jensen, 1994].

5.2.9 Activation of smoke control system

Fire experience onboard ships shows that fire in cabin areas can develop extremely quickly. Further, experience shows that fires in cabin areas onboard passenger ships often start as smouldering fires. A smouldering fire develops only a small quantity of heat and is, consequently, not detected by heat detectors/sprinklers, before it develops into a flaming combustion. It may take a long time before this happens. During this time the smouldering fire may have developed large amounts of smoke containing dangerous gases and will then be a big risk for the passengers. Therefore, it is very important to fight the fire as quickly as possible.

Bearing this in mind, and considering the fact that smoke detectors are to be installed all over the accommodation, the addressable smoke detection system should be capable of activating the smoke control system. If the smoke detectors are suitably placed, this solution will give the shortest reaction time in case of fire [Jensen, 1994].

5.2.10 The control system

The smoke control system is to be an integral part of the HVAC control system. Further, the system is to be connected to a fire detection system, including the smoke detection system, so that signals from here can be used for activating the smoke control system [He, et al., 2002].

After having received and interpreted signals coming from the fire detection system the smoke control system proposes a pre-programmed control action. When the action performed by the smoke control system does not correspond to the required action, that is, in case of a fan breakdown – an alarm will be triggered. All alarms must be audible.

The system must allow the crew to override manually the actions suggested by the smoke control system at any time. Misunderstandings by the crew have to be avoided. The control system and all the components (fans, dampers, etc.), activated by the system in a fire situation, must be connected to the emergency generator [Jensen, 1994].

5.2.11 Abbreviated draft guidelines

Fire Prevention (FP) 40 in 1995 established draft guidelines for approval of active smoke control and ventilation systems in passenger ships [Abell, 1999]. These include:

1. The main objective of an Active Smoke Control System (ASCS) is to keep the escape routes free from smoke for escape and aid to fire fighting operations.

2. Passive Smoke Control means the utilisation of built in barriers within the ship such as main vertical bulkheads, fire doors and fire dampers in order to enclose the fire area and stop the spread of smoke.

3. Active Smoke Control uses mechanically created pressure differentials and flows between smoke control zones to prevent smoke spread and remove smoke from the ship by extraction.

4. Staircases shall be kept over-pressurised to prevent smoke rising up staircases.

5. An ASCS shall operate within two minutes of detection.

Many other points were drafted including design, types of spaces, test procedures and performance criteria, which were submitted by the correspondence group who were also concerned with the technical understanding of a smoke control system on board [Abell, 1999].

5.3 A Proposed Approach

The general smoke control philosophy is described as follows:

1. Special smoke extract fans extract the smoke through grilles installed in the ceiling in corridors on the burning deck in the fire zone. This means that there will be a negative pressure in the corridor.

2. All cabins belonging to the fire zone on the deck on fire are to be continuously supplied with air. Supplying air into the cabin creates a positive pressure in these spaces.

3. In order to avoid spread of smoke from the burning zone to adjacent stairwells, these spaces are to be pressurised.

It should be emphasised that it is not possible to create a smoke control system that is capable of stopping the spread of smoke from any fire, irrespective of size or development. There is no guarantee that the smoke extraction can be used to maintain a clear layer of air; this depends on the burning material, the size of the fire, etc. In case of fire in a corridor the smoke control system must work exactly in the same way, as just described previously [Jensen, 1994].

The conditions of pressure in cabin, corridor and stairs are shown in Figure 5.3. It can be seen that in cabins and stairs, there is a positive pressure while in corridors, there is a negative pressure.

Several full scale tests have been carried out successfully according to the smoke control philosophy described previously [Jensen, 1994]. The disadvantage of this smoke control system is that the smoke from the cabin on fire enters the corridor whilst the smoke will rise towards the ceiling and – depending on the smoke production and the extracted air volume – will mainly be concentrated between the two adjacent exhaust grilles. Tests, which have been performed, have also shown this. Further, as previously mentioned, large quantities of heat and toxic smoke will be extracted [Jensen, 1994].

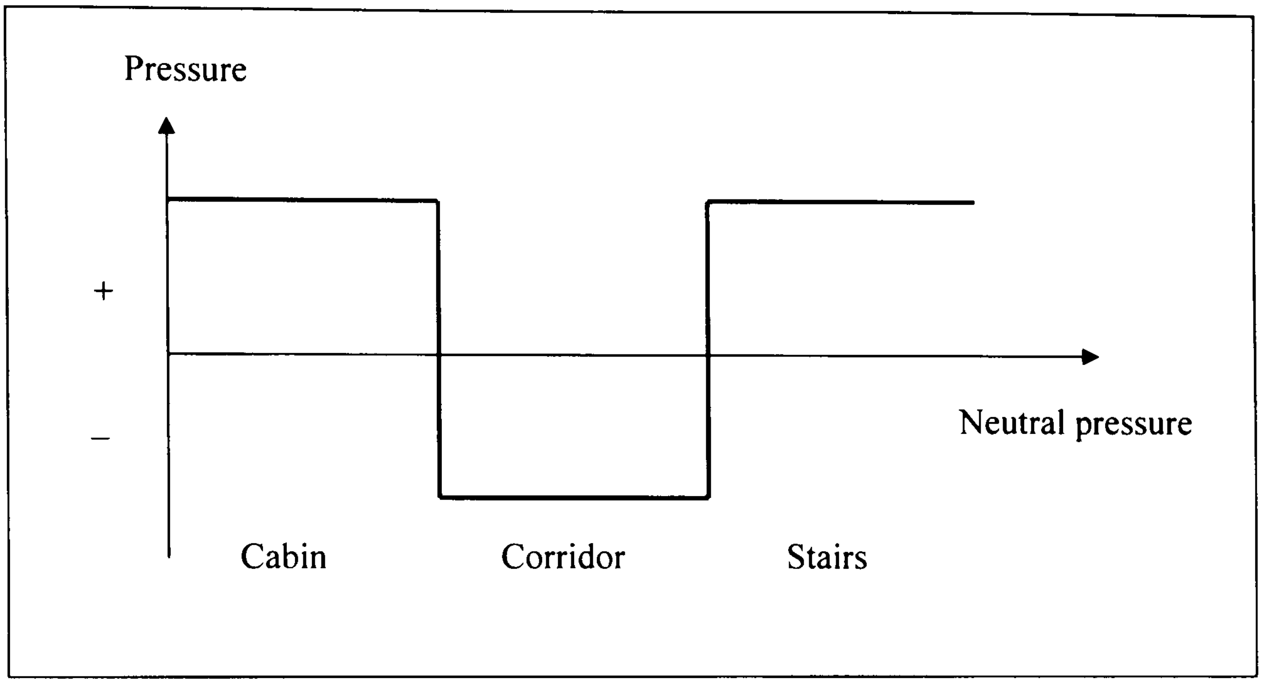


Figure 5.3. Pressure conditions during smoke control mode.

Smoke control will be a much better solution than previously described when the HVAC systems were shut down in a fire situation. Further, the advantage of this proposal is that to a large degree the traditional HVAC systems utilised are supplemented with only a few special components, such as, for instance, special smoke extractor fans.

Air supply at the ceiling in the corridor of the burning zone must be avoided in a fire situation. This will result in mixing of air and smoke, which may cause considerable reduction of visibility in the lower part of the corridor. If there is only extraction in the ceiling and the air supply comes, for example, from grilles in the lower part of cabin doors, a smoke layer at the ceiling is produced.

Due to the very limited space above the ceiling in the corridors it will, in practice, be very difficult to have two different exhaust ducts – one for normal operation the other for smoke extraction.

Unless the forthcoming regulations will require two sets of exhaust ducts, one exhaust duct in the corridor serving both operations could be used. In order to install as few smoke extraction fans as possible, an extra exhaust duct can be installed in the trunk – a duct for smoke extraction only. The duct for smoke extraction is connected to the corridor exhaust ducts on all the accommodation decks in the main vertical fire zone.

In case of fire, the damper between the duct(s) for normal extraction and the exhaust duct in the corridor on the burning deck closes, and the damper between the duct for smoke extraction and the exhaust duct(s) in the corridor in the burning accommodation area opens. All ducts for smoke extraction are to be heat insulated.

Supplying air into the cabins creates a positive pressure in these spaces. This ensures that the smoke is kept out of those cabins not on fire. Further, supply of air into the cabins ensures that smoke will not pass from the burning cabin into other cabins via the duct system.

The passage of smoke between the cabins via exhaust ducts from the bathroom must also be prevented – either by extraction or supply through the system. In order to secure positive pressure in the cabin, it must be ensured that the air volume, which may be exhausted via the ducts in the bathroom, is always smaller than the air volume, which is supplied to the cabin.

In this connection it should also be mentioned that in case of a smoke control operation immediate shutdown of the recirculating air is required. Consequently, the return air dampers in the air-handling units are to be equipped with remote control connected to the control system.

Smoke detectors are to be installed in the supply part of the system. The supply fan is to be equipped with remote control connected to the control system. In case of smoke detection immediate shutdown of the supply fan is required in both normal and smoke extraction modes.

Discharge of smoke ought to take place without the risk of smoke being sucked into the inlet grilles. Therefore, discharge should take place vertically at the top of the ship.

It must be ensured that the components of the smoke control system can withstand high temperatures. The authorities have to define these temperatures in the regulations. The audible alarms in corridors must be sufficiently loud to drown the noise from smoke extraction. These are some of the requirements, which the authorities have to implement in the regulations regarding smoke control.

In order to maintain the escape routes (stairwells and halls) free of smoke, the use of a mechanically driven extraction system to remove any smoke that may have entered the escape route is not satisfactory. An extraction system will reduce the pressure level in the escape route. Consequently, more smoke will be drawn into the escape route and visibility will be reduced, rather than improved.

To prevent the smoke from entering the stairwells and halls an adequate air flow, which will keep the smoke away from spaces, is needed. To obtain this air flow air is to be injected into the area. The air leaks out of the space via door cracks, by a specially provided opening or into the fire area, where it is extracted. This system is called 'pressurisation', because in order to set up the required air flow the pressure in the escape routes is raised [Jensen, 1994].

In connection with the design of the smoke control system, it is most important that the authorities consider to what extent fire doors are automatically released into the closed position when a fire is registered. Automatic closing of fire doors has been investigated and is expected to become an IMO requirement [Jensen, 1994].

In case of closed fire doors the door opening forces resulting from the pressure differences produced by the smoke control system and the door closers must be considered. Over-pressurisation must be prevented because unreasonably high door opening forces can result in escaping passenger having difficulties or being unable to open doors to the escape routes.

As a point of information it should be mentioned that the National Fire Protection Association (NFPA) states that the force required to open any door in an escape situation is 100 N (UK) and 130 N (USA) [Abell, 1999].

Some methods to achieve pressure control are:

1. To supply air fan and damper reliefs.

2. To supply air fan with variable speed.

3. To supply air fan with by-pass dampers.

Water spray from sprinklers cools the smoke and reduces the pressure differences due to buoyancy. Some of the literature recommends a minimum pressure difference of 10 Pa in this case [Abell, 1999]. Pressure differences across the fire door near the injection point can also be excessive, making the door difficult to open. On the other hand pressure difference far from the injection point can be minimal and may therefore fail to prevent smoke infiltration. The flow resistance in the stairwell causes the variation in pressurisation. This means that the stairwell pressurisation system shall be designed with multiple injection points.

Another problem is the intermittent loss of effective pressurisation that occurs when the escaping passengers enter and leave the stairwell during evacuation. The pressurisation system should have a supply fan with sufficient capacity to provide effective pressurisation to prevent smoke entry when doors are open. For the design of the stair pressurisation system the number of doors that can be opened simultaneously should be considered. A design that allows all doors to be open simultaneously may ensure that the system always works, but it will probably add to the cost of the system.

If all the fire doors leading to the burning zone are closed in case of fire it must be ensured that adequate replacement air is supplied into the burning zone. Depending on the smoke volume that has to be extracted, it may be necessary to install duct(s) in the trunk leading directly to open air. An alternative is to install an extra supply fan used for the smoke control operation only.

The extracted smoke mass flow varies with the temperature of the smoke. Consequently, the speed of the above mentioned supply fan must be controlled by the control system. Unless adequate air is supplied there is a risk that the smoke extraction will create a huge negative pressure in the corridor. As a result of this, it may be impossible for the escaping passengers to open the fire doors, depending on which way the doors open. In order to prevent such a situation, the authorities ought to require that fire doors between corridor and stairwell will open into the corridor. Correctly there are no IMO regulations stating whether fire doors are to open into the corridor or out into the stairwell.

If the fire doors are open it is possible to take advantage of the air flow coming from the pressurised stairwell. In case of open fire doors the extra supply fan with variable speed or the duct leading to open air is, in this case, not needed [Abell, 1999].

The requirements given by the authorities regarding design of pressurisation systems must include: a required minimum and allowable maximum pressure difference between corridor and stairwell; a minimum air flow velocity through open fire doors; and the number of doors that are open simultaneously.

In this study, the ASCS is compared with the other two cases (i.e. HVAC system is stopped and HVAC system is normal) in terms of smoke layer heights in the corridor, given the occurrence of a fire in the cabin. To carry out this the following steps are proposed:

Step 1 Present the available data and make appropriate assumptions. In this step, the number of the cabins needs to be defined. The accommodation zone needs to be specified. The dimension of the corridor and fire load also need to be specified.

Step 2 Describe the ventilation system. In this step, it is required to define geometric characteristics of the door openings and mechanical ventilation supplies.

Step 3 Use a deterministic simulation through the fire zone model implemented in FAST (Fire growth And Smoke Transport) computer code [Peacock, et al., 2000] to study smoke layer heights. In this step, the data obtained in Steps 1 & 2 can be fed into the FAST software. Each of the three cases is studied individually to obtain the characteristics.

The fire simulation shall demonstrate the possible burden and pollution created from smoke, temperature and toxic loads in the ship spaces. Among other mathematical modelling possibilities, so called "zone models" are available, which constitute a simplified balance model of energy and mass flow, and offer a numerical solution. With zone models it is possible today to reliably predict the spread of smoke layers and the development of gas temperature, and to characterise with some degree of accuracy the visual range within the smoke [Schreiter, et al., 2003]. Zone models have been used since the mid 1970s to predict thermal hydraulic conditions in a fire compartment prior to flashover. The zone model approximation treats the compartment atmosphere as two well mixed layer. Such stratification often arises as a result of buoyancy, but may be inapplicable in certain situations such as tall stairwells, long corridors or other situations where three dimensional effects are important. Zone models apply conservation equations to each layer, with the user specified fire providing a source of energy and mass [Ramsdale & Mawhinney, 2003].

The computer model FAST can be used to simulate physical conditions inside the building during a set of predetermined fire scenarios. Zone models such as FAST are relatively easy and quick to use and provide a reasonable engineering estimate of smoke hazards in compartmented structures [He, et al., 2002].

Step 4 Analyse the results. The results obtained are compared in terms of smoke layer heights. Comments on the three cases are made.

5.4 Case Study

Step 1

The following are the basic available data and assumptions:

1. A Main Vertical Zone (MVZ) in a passenger ship compliant with the SOLAS Convention as amended in 1997.

2. 10 cabins per deck

Passenger cabin's area is (6m×3m), containing a trash can, an upholstered chair, a bed, a table, a wardrobe and a bathroom (2m×2m) and provided with low flame spread covering as per SOLAS II-2.Reg.34.3 [IMO, 1997].

3. Total length of corridor: (15m ×1.5m) per deck

4. Fire load

At first, the only presence of an upholstered chair was assumed to screen the most relevant and critical event sequences. This allows applying the Heat Release Rate (HRR) reference curve obtained by laboratory tests with the furniture cone calorimeter [US Department of Commerce, 1983, 1985, 1988].

The model characteristic values are:

- Fire growth rate: $\alpha = 0.1055$ kW/s^2, that is "fast" according to SFSE [SFPE, 1993] and between "fast" and "ultra-fast" according to the BSI Standards [IMO, 1997].
- Peak value: t = 140s, Q = 2.11 mW.
- Transition to decay at t = 160s.
- End combustion at t = 500s.
- Total heat developed = 372 mJ [Angelo & Giovanni, 1997].

The chair was assumed to be in a corner of the room.

Step 2

1. Ventilation

The cabin is equipped with a self-closing door as per the SOLAS regulations [IMO, 1997] and a window (with no restrictions about its constituting material), depending on the cabin row.

The door is not airtight, and therefore it was assigned a leakage even when closed.

The window is made of standard materials and for this reason, it was assumed unable to withstand the fire. This implies the window to be either open or broken, in those scenarios when it is present.

To take into account the natural ventilation (including leakage through the door), the following geometric characteristics of the openings were assumed:

- Door open: 0.6m × 2.0m.
- Door closed: 0.01m × 2.0m.
- Door grill: 0.2m × 0.4m, sill 0.2m.
- Window open: 1m×1m, 1m from the floor.
- Window closed: 0.01m×1m.
- Ceiling height: 2.44m.

Figure 5.4 has the following characteristics [Abell, 1999]:

- Air outlet: 250m^3/h per cabin.
- Ceiling extraction bathroom: 50m^3/h.
- Ceiling extraction corridor: 3m^3/s.

2. It was assumed that the smoke detector and sprinkler do not activate.

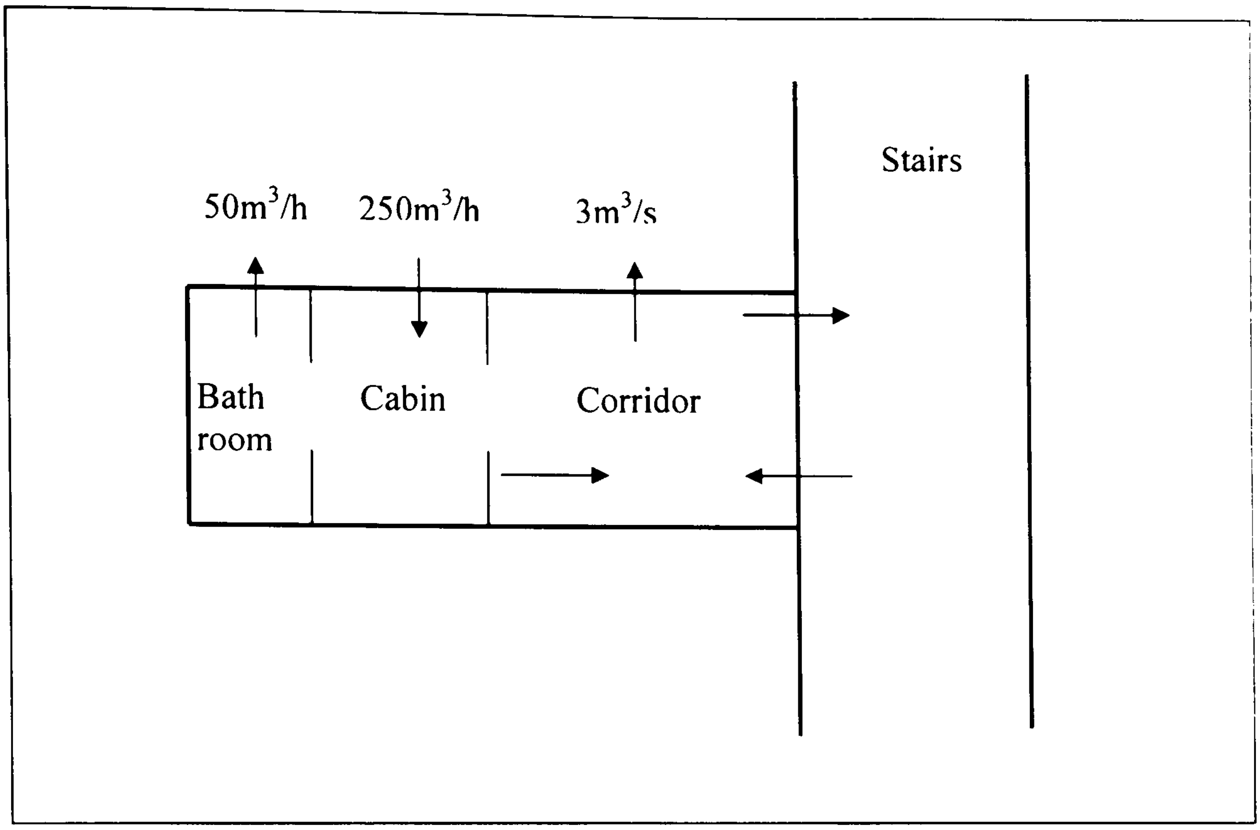


Figure 5.4. Mechanical ventilation supplies air values.

Step 3

Test 1

For this test 1, the initial fire occurred in an upholstered chair corner of cabin (compartment 1). The smoke then fills the corridor and venting in next cabin (compartment 3). Cabin and corridor ventilation (HVAC System) is stopped.

The evaluation of the test 1 consequence (**Smoke Layer Height after 1min**) was accomplished by means of a physical simulation using the FAST code. The result is shown in Figure 5.5.

In a similar way, test 2 and test 3 are studied.

Test 2

Cabin and corridor ventilation (HVAC System) is normal.

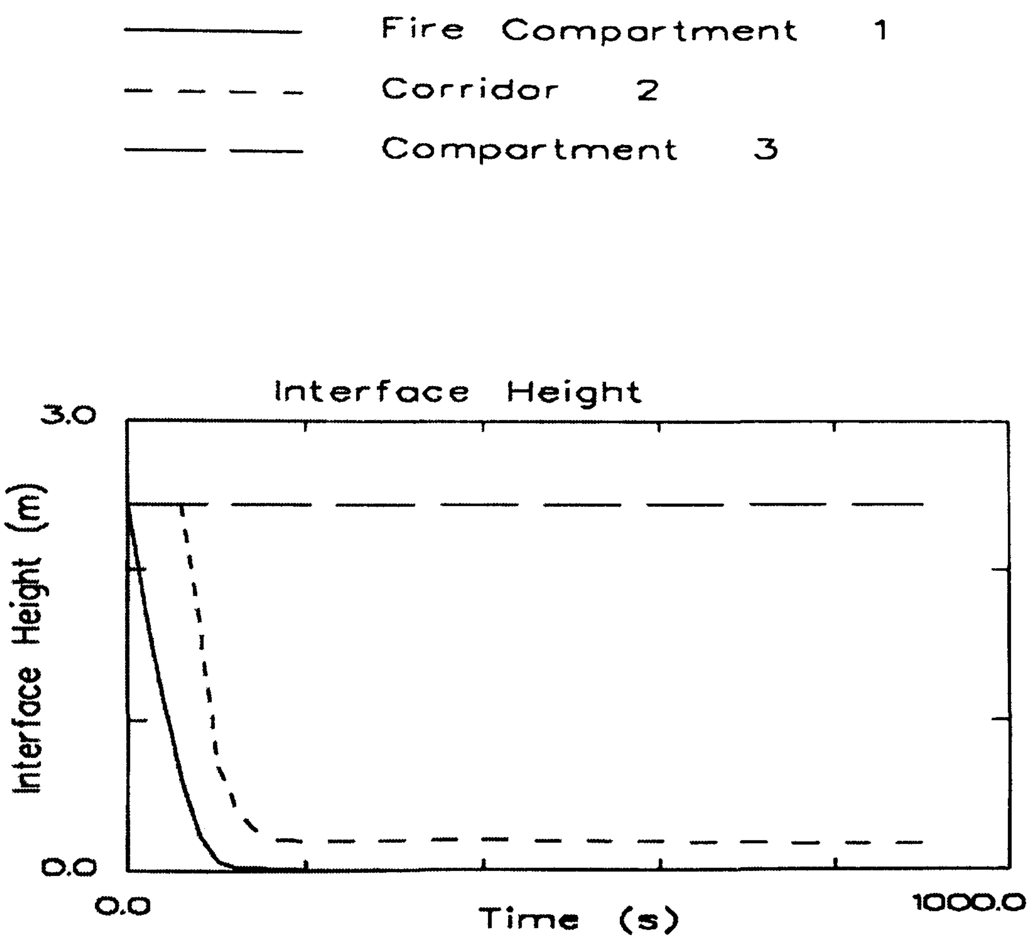


Figure 5.5. Test 1 result of smoke layer height.

Test 3

ASCS is working. The following information is given:

- Ceiling extraction bathroom: 100m^3/h.
- Ceiling extraction corridor: 6m^3/s.

Step 4

Results

Test 1 (After 1min, Corridor Smoke Layer Height= 2.01m)

The calculation shows that if the ventilation is stopped the corridor becomes smoke logged. Smoke overflows to stairs.

Test 2 (After 1min, Corridor Smoke Layer Height= 1.36m)

If the ventilation is kept in operation the smoke level is not significant and is contained at the corridor ceiling.

Further comments following test 2 indicated that smoke in the corridor is limited and would not give great difficulties in passenger evacuation provided that the ventilation is kept running.

Test 3 (After 1min, Corridor Smoke Layer Height= 1.03m)

When the ASCS is kept in operation the smoke level is much lower. Smoke spillage is limited to stairwell.

The result of the smoke layer height for each test case is shown in Figure 5.6.

This appears to be over optimistic. All tests have to begin with a selected size of fire and even slight variances, in reality, could change results.

Any smoke, which is detected in crew or passenger spaces means that immediate evacuation is essential.

5.5 Conclusion

IMO is a well intentioned authoritative body, but in the past, by the nature of the organisation's procedures, acceptance of regulations internationally was slow. Although this process has been speeded up, technological advances and general developments often overtake regulatory requirements.

The actual design and operation of ASCS does vary on the newer vessels but essentially it is the risk to life that is the concern of this chapter rather than tactical ventilation during fire fighting.

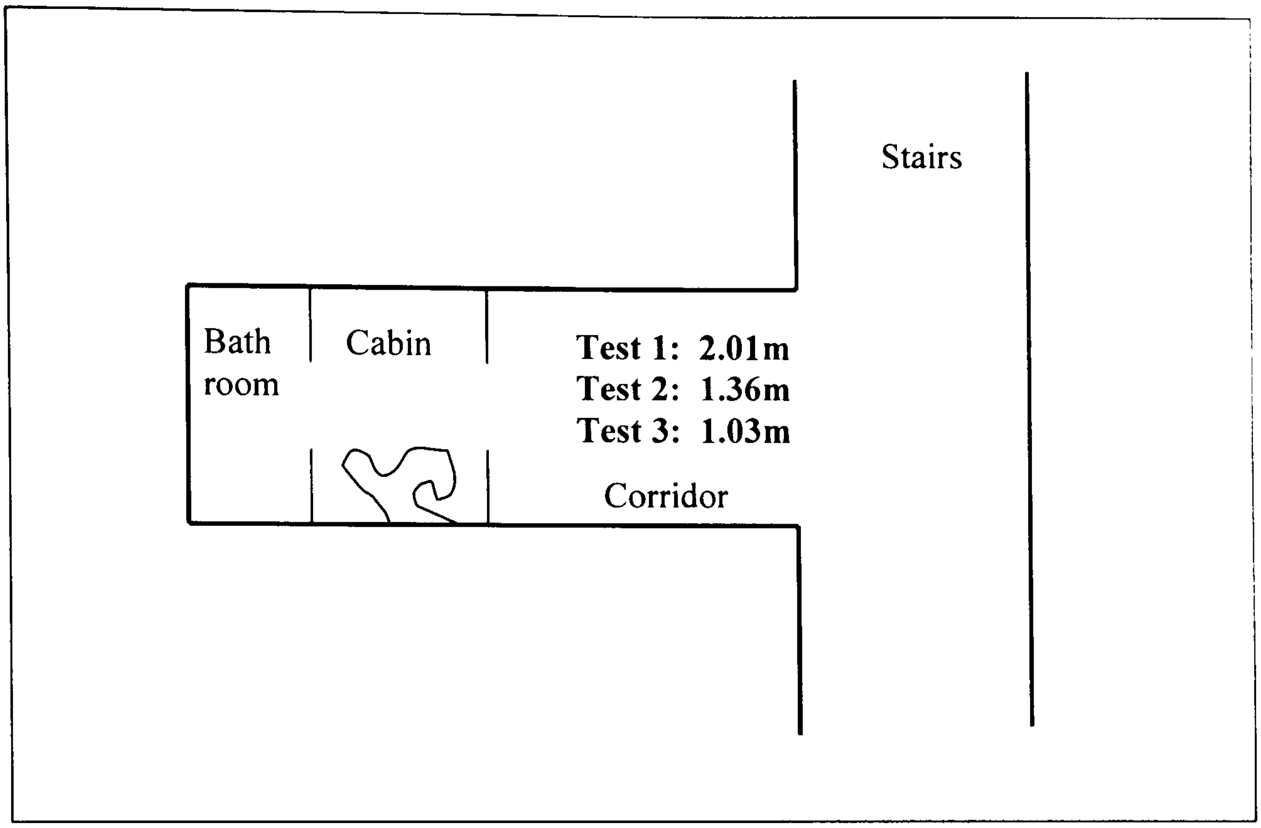


Figure 5.6. Test results of smoke layer height.

Some of the new vessels, due to come into operation soon, have the following systems built in:

If a fire is detected in any cabin,

1. The air supply fan automatically stops and its dampers close.

2. The recirculating air fan stops and its dampers close.

3. The exhaust fan from the bathroom continues to extract.

It is possible that smoke from a cabin may enter stairwells such that the escape by personnel from different decks may be compromised. In this case:

1. The recirculation damper closes.

2. The relative fan speeds of the stairs supply and stairs exhaust change to a predetermined point to create an over pressure from the stairs into the corridor.

The ship designer has a considerable problem in incorporating everything that is required or expected for passengers. Assistance, during an emergency, may be non-existent so everything that ensures the safety of the passengers and crew is essential. Smoke is one of the main killers at sea and this simple fact has been known for many years.

The previous disasters proved to be an awakening and still there are a few regulations to put in place to deal with the problems that the chapter has brought to light. The regulatory process must be cautious but that also means it is ponderously slow. In this chapter different philosophies and solutions on smoke control have been discussed. The current regulations do not address the issue of smoke control in passenger ships as well as they should. IMO and other regulatory authorities could usefully benefit from using the techniques assessed in this chapter to improve smoke control in these vessels. These include:

1. The smoke which has to handle all relevant data such as smoke volume to be extracted and smoke temperature.

2. Required minimum and allowable maximum pressure differences between corridors and stairways.

3. Criteria for temperature resistance of smoke extraction equipment.

4. Definitions and functions of the control system.

References

Abell, J. (1997), "Smoke and Human Behaviour – A Lethal Combination!", Fire At Sea, RINA, London, UK, 20-21 November.

Abell, J. (1999), "Developments in Active Smoke Control Systems for Passenger Vessels", Learning from Marine Incidents, RINA, London, UK, 20-21 October.

Anderson, P., Robertsson, H. & Wikman, J. (1993), "A Fire Safety Survey of Materials Used in Passenger Vessels", Accommodations, Research Report MariTerm AB, ISBN 91 630 1809N, Goteborg Sweden, 8 April.

Angelo, T. & Giovanni, G. (1997), "Fire Risk Analysis on Cruise Ships – Application to an Accommodation Zone", Paper 3, Fire at Sea, RINA, London, UK, 20-21 November.

Chow, W. K. (1995), "A Comparison of the Use of Fire Zone and Field Models for Simulating Atrium Smoke-filling Processes", Fire Safety Journal, Vol 25, pp 337-353.

Chow, W. K. (1997), "On the Use of Time Constants for Specifying the Smoke Filling Process in Atrium Halls", Fire Safety Journal, Vol 28, pp 165-177.

Fu, Z. & Hadjisophocleous, G. (2000), "A Two-zone Fire Growth and Smoke Movement Model for Multi-compartment Buildings", Fire Safety Journal, Vol 34, pp 257-285.

Graham, A. (1995), "Smoke Movement Driven by a Fire Under a Ceiling", Fire Safety Journal, Vol 25, pp 261-275.

He, Y. & Beck, V. (1997), "Smoke Spread Experiment in a Multi-storey Building and Computer Modelling", Fire Safety Journal, Vol 28, pp 139-164

He, Y., Wang, J., Wu, Z., Hu, L., Xiong, Y. & Fan, W. (2002), "Smoke Venting and Fire Safety in an Industrial Warehouse", Fire Safety Journal, Vol 37, pp 191-215.

IMO (1997), "SOLAS, Consolidated Edition", London, UK.

Jensen, K. H. (1994), "Smoke Control in Cruise and Passenger Vessels", Paper 13, IMAS 94, Fire Safety on Ships, Developments into 21st Century, London, UK, 26-27, May.

Kim, M. B., Han, Y. S. & Yoon, M. O. (1998), "Laser-assisted Visualization and Measurement of Corridor Smoke Spread", Fire Safety Journal, Vol 31, pp 239-251.

Peacock, D. R., Reneke, A. P., Jones, W. W., Bukowski, W. R. & Forney, P. G. (2000), "A User's Guide for FAST: Engineering Tools for Estimating Fire Growth and Smoke Transport", NIST (National Institute of Standards and Technology), Special Publication 921, USA.

Ramsdale, S. & Mawhinney, R. N. (2003), "Fire Consequence Modelling for the Safety First Project", Passenger Ship Safety, RINA, London, UK, 25-26 March.

Schreiter, J., Voelker, J. M., Nusser, S. & Meyer-König, T. (2003), "Demonstrating Regulatory Compliance of Alternative Designs a Framework Concept", Passenger Ship Safety, RINA, London, UK, 25-26 March.

SFPE (1993), "The SFPE Handbook of Fire Protection Engineering", Society of Fire Protection Engineers, National Fire Protection Association, USA.

US Department of Commerce (1983), National Bureau of Standard, National Engineering Laboratory, "Fire Performance of Furnishings as Measured in the NBS Furniture Calorimeter, Part 1", NBSIR 83-2787, USA.

US Department of Commerce (1985), National Bureau of Standard, National Engineering Laboratory, "Effect of Wall and Room Surfaces on the Rates of Heat, Smoke and Carbon Monoxide Production in a Park Lodging Bedroom Fire", NBSIR 85-2998, USA.

US Department of Commerce (1988), National Bureau of Standard, National Engineering Laboratory, "An Experimental Data set for the Accuracy Assessment of Room Fire Models", NBSIR 88-3752, USA.

CHAPTER 6 - EVACUATION ANALYSIS OF PASSENGER SHIPS: USING COMPUTER SIMULATION TO PREDICT EVACUATION PERFORMANCE

Summary

Several disasters with passenger/Ro-Ro vessels over the last years have demonstrated a need for evacuation analysis. This chapter presents a methodology for modelling an evacuation. Ship evacuation models offer the promise to quickly and efficiently bring evacuation considerations into the design or modify an existing design phase. Typically, this chapter provides the simulation of 90 passengers and 10 crew members mustering on a vessel of 6 decks. After this, simulation of different scenarios is discussed.

6.1 Introduction

Recent well-published disasters of passenger/Ro-Ro ships together with trends of largely increased capacity of passenger carrying ships have brought the issue of effective passenger evacuation, being the line of defence, in an emergency to the centre of attention of the maritime industry worldwide. With numbers now ranging up to 6,000 on a single large cruise liner, with ships often trading in pristine environmental areas and with rapidly growing consciousness for safety and environmental protection among ship operators, assurance of all these issues at the highest levels has become the main targets for technological innovation in the maritime industry as well as key factors for gaining and sustaining competitive advantage [Simões, et al., 2000]. However, the process of evacuating a large passenger ship is a very complex one, not least because it involves the management of a large number of people on a complex moving platform, of which they normally have very little knowledge. These characteristics make ship evacuation quite different to evacuation from airplanes and buildings [Shields & Boyce, 2000] as the first only involve relatively simple geometries, whilst the second imply steady platforms, normally with no need for assistance to be given to its occupants during an evacuation and no need for their preparation to survive a harsh environment following a successful evacuation. These inherent problems, coupled to limitations in time to the extent that evacuation may often be untenable, render decision making during a crisis a key to successful evacuation and any passive or active support encompassing design for ease of evacuation, crew training, evacuation plans/procedures and intelligent systems onboard critically important [Lopez & Perez, 2003].

Following a ship incident, a decision has to be taken as to whether an evacuation is necessary. In many situations the safest course of action is to remain onboard the ship as the environment outside can be more perilous than that on board [Rutgersson, et al., 2003]. In such cases the evacuation does not require passengers to abandon ship but to seek safe refuge away from the immediate threat. However, uniquely to shipping applications, the orientation of the escape paths may be time dependent due to roll [Galea, 2000, Galea, et al., 2002, Galea, et al., 2004, Gwynne, et al., 2001].

Uniquely to ship situations, a good deal of time consuming preparatory activities must be completed prior to the actual evacuation. Passengers are instructed to collect life jackets (usually located in cabins or muster stations) and are usually further required to assemble in pre-defined muster stations prior to attempting to disembark. Even in the well-orchestrated Exercise INVICTA, the mustering operation required between 11 and 20 minutes [Marine Safety Agency, 1996, Thompson & Wheatley, 2000]. In addition, family groups separated prior to the emergency are likely to attempt to reunite prior to attempting to evacuate, all of which effectively delays and prolongs the evacuation process. Again uniquely to shipping situations, for the majority of passengers, the evacuation path is often counter intuitive. In buildings where the way out of a structure is to normally proceed to street level, while on board ship the way off requires passengers to seek the muster station. This could require passengers to travel to an apparently arbitrary location above or below their current position and to the port or starboardside. Furthermore, the routes can be complex and confusing to passengers not accustomed to the marine environment, even the term "muster station" may be unfamiliar to some passengers [Koss, et al., 1997].

Throughout the evacuation process complex contra-flows can develop within the passageways and staircases. These can be formed by flows of passengers with different goals, for example by passengers attempting to find companions, collect life jackets and warm clothing and locate muster stations. Crew can also create contra-flow situations as they attempt to tackle the cause of the emergency or reach assigned duty stations. Regardless how remote the possibility or difficult the task, ship evacuations do occur and they can be the result of fire (e.g. Ecstasy), collision (e.g. European Gateway), grounding (e.g. Saint Malo Ferry), equipment failure (Estonia) or human error (Herald of Free Enterprise) [Glen, et al., 2003].

6.2 Background

A number of drivers have brought passenger evacuation to the forefront of priorities of the European shipbuilding industry triggering the need for the development of tools [Soma, 2001] and procedures in support of performance-based design for evacuation to ensure cost-effective treatment of this important issue:

1. Passenger ship/Ro-Ro ferry accidents have brought about the realisation that "ship and cargo survival" might have to be addressed separately from "passenger survival" in that these vessels can capsize very rapidly, when damaged, thus not allowing sufficient time for evacuating passengers and crew.

2. An amendment to SOLAS (Safety Of Life At Sea) '74 requires "Ro-Ro passenger ships constructed on or after 1 July 1999, to have escape routes evaluated by an evacuation analysis early in the design process".

3. The consequences of accidents involving large loss of lives could drive shippers out of business, as the Estonia tragedy has amply demonstrated. Such consequences are bound to reach intolerable levels when addressing new concepts such as cruise liners carrying well over 5000 passengers.

Deriving from the above, there is an immediate need to address the capability of the whole passenger evacuation system pertaining to mustering routes and procedures, life-saving appliances [Rodricks & Cooke, 1996], decision support and management. In turn, this leads to the necessity to focus on the development of evacuation analysis and simulation tools for the prediction of evacuation performance, thus allowing for a meaningful evolution of passenger ship designs with enhanced evacuation performance (minimum time for safe evacuation of passengers and crew). Successful mustering and evacuation can avert disaster as the last lines of defence even after the safety measures linked to structural reliability and enhanced ship survivability have failed. In this respect, the development of tools in the form of computer simulation models for the prediction of evacuation scenarios, evacuation time and probability of success in different conditions must be addressed as a top priority. The same tools could also be used to aid decision making onboard the ship, thus tackling the same problem as an operational rather than a design issue [Vassalos, et al., 2002].

6.2.1 The shipboard evacuation problem

Much as there are generic elements in the simulation of passenger evacuation equally applicable to ships, buildings or aircraft, there exist critical differences between them, which are likely to have a significant (and hence crucially important) effect on the outcome that ought to be addressed at the outset [Majumder, 2000].

6.3 Methodology

An evacuation analysis framework is proposed to include the following steps:

1. Collection of information.

2. Simulation of evacuation process.

3. Simulation of the consequences.

They are detailed in the following:

1. A wide range of developments concerning design and operational "tools" have been made possible including:

   1) Evaluation of evacuation time for certification purposes.

   2) Design/modification for ease of evacuation. This involves systematic parametric investigation to identify governing parameters of the ship environment (e.g., corridors, staircases, number and location of mustering stations, life saving appliances, signage) within a pre-defined set of human behaviour parameters and mustering and evacuation procedures. This would allow design optimisation for enhancing evacuation performance, where parameters being considered include: evacuation time and components contributing to it; time history of occupancy of regions of interest; queue size time history (bottlenecks); rate of crossing through doors, etc.

   3) Mustering/evacuation routes and procedures. This involves the identification of optimal passenger flow (minimum total evacuation time) concerning choice of routes and procedures to achieving this. Heuristic approaches based on experience and engineering judgement are used in combination with self-searching and tuning algorithms to automate this process.

   4) Crisis management and decision support. This involves development of effective management and decision support systems for risk containment during a crisis as active means to averting catastrophes (e.g., an onboard evacuation simulation platform to aid decision-making for effective mustering/evacuation in a range of incidents).

   5) "What if" scenarios for crew training.

   6) Passenger familiarisation with a ship's environment – particularly the large cruise liners and passenger/Ro-Ro vessels being built today.

2. The evacuation when applied to maritime applications refers to all that activity which takes place from the sounding of an alarm to leaving the ship. To truly model ship based evacuation it is essential to address all of components. To perform the required simulation reliably requires an evacuation model with the appropriate set of capabilities and access to the necessary data. Furthermore, the scenario under consideration may be under conditions of calm or involve situations with list or roll [Tsychkova, 2000]. This will affect not only the nature of the data required but also the capabilities of the model. When modelling human behaviour during evacuation it is essential that the enclosure geometry, population and population behaviour be represented.

3. The simulation produces a range of output, both graphical and textual. Interactive two-dimensional animated graphics are generated as the simulation is running. This allows the user to observe the evacuation as it takes place. The graphics are interactive allowing the user to interrogate occupants and events. In addition, a data output file is produced containing all the relevant information generated by the simulation, including a copy of the input data. For example, the output data includes evaluation time need for individuals, total time to muster and evacuation, distance travelled by individuals and time wasted in congestion by individuals. These are intended to be used once a simulation has been completed and enable large data output files to be searched and specific data selectively and efficiently extracted.

6.4 Case Study

A typical page during the evacuation involving fire of 90 passengers and 10 crew members from a passenger ship with some of the controls available in the simulation software is shown in Figure 6.1.

In this case, the evacuation analysis is carried out by means of a deterministic simulation through a multi-decks model implemented in the *Evi* [Vassalos, et al., 2001a-c]. In particular, the simulation of every scenario yields results in terms of total travel time (evacuees arriving at embarkation station).

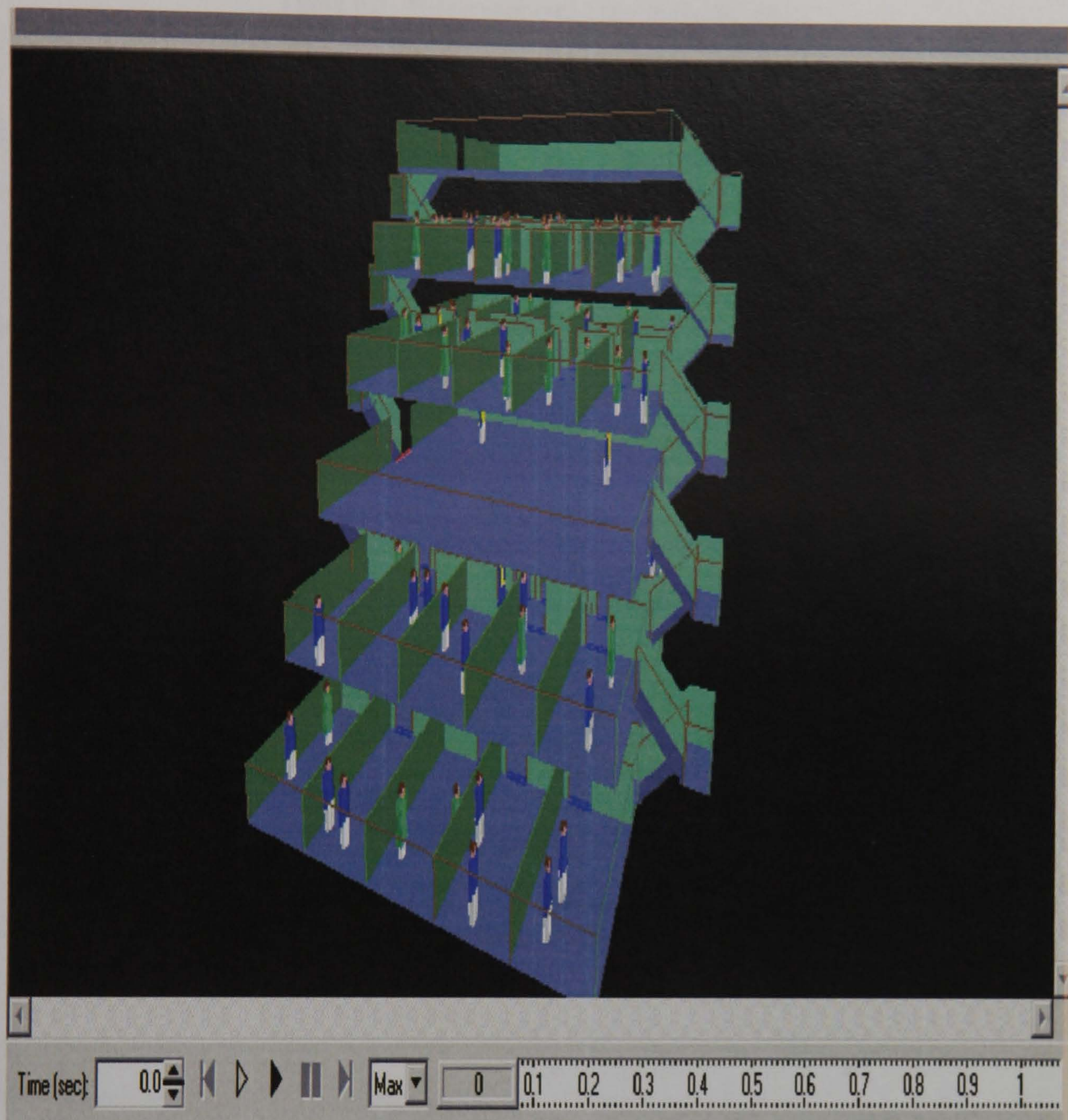


Figure 6.1. *Evi*: Run time simulator during an evacuation.

To demonstrate the use of the simulator, a number of scenarios are considered for a passenger ship operating in international waters. The vessel consists of 6 manned decks – 4 of which contain cabins. Each cabin size is 6m×3m×3m. The assembly station is located within a centralised atrium on deck 3. The embarkation station is located on deck 6. The detailed passenger and crew distributions are shown in Table 6.1.

Table 6.1. Passenger and crew distributions.

Deck	Number of cabins	Number of passengers	Number of crew	Remarks
1	10	20	2	Cabins
2	10	20	2	Cabins
3			2	Assembly station
4	10	20	2	Cabins
5	10	30	2	Each cabin for 3 passengers
6				Embarkation station

The decks are connected by staircases and the width of each corridor is 2m, the location and dimensions of which are given in Table 6.2.

Table 6.2. Deck connectivity by stairs.

Connecting deck	Number of staircases	Width	Remarks
1 – 2	2	1 m	
2 – 3	2	1 m	4 – Fire doors
3 – 4	2	1 m	
4 – 5	2	1 m	
5 – 6	2	1 m	4 – Fire doors

There are no arrows indicating the main escape route – this is due to the fact that there is always an option of two routes to the assembly/embarkation station (such as onboard *Scandinavian Star* where some passengers ended up entering areas affected by the fire by following EXIT arrows). Instead of arrows, the corridors in accommodation areas are marked by LLL (Low Location Lighting), luminous green horizontal lights along the length of the corridor and vertical lights marking doorframes along the escape routes.

Information on passenger and crew distribution and demographic details was obtained from the IMO Interim Guidelines. All cases randomised passenger and crew gender. The simulations were run with passengers present in their cabins at the start of the simulation involving fire, which is referred to as 'night case' in the IMO Interim Guidelines. A 'day case' is one where passengers are situated in public areas (e.g. restaurants, shopping mall, etc.) [IMO, 2002].

Case 1: From Cabin to Assembly Station

At the sound of the general alarm the passengers start moving from their respective cabins to the assembly station. Reaction time and uncertainties concerning age and gender, which affect speed of advance, are assigned (see Figure 6.2).

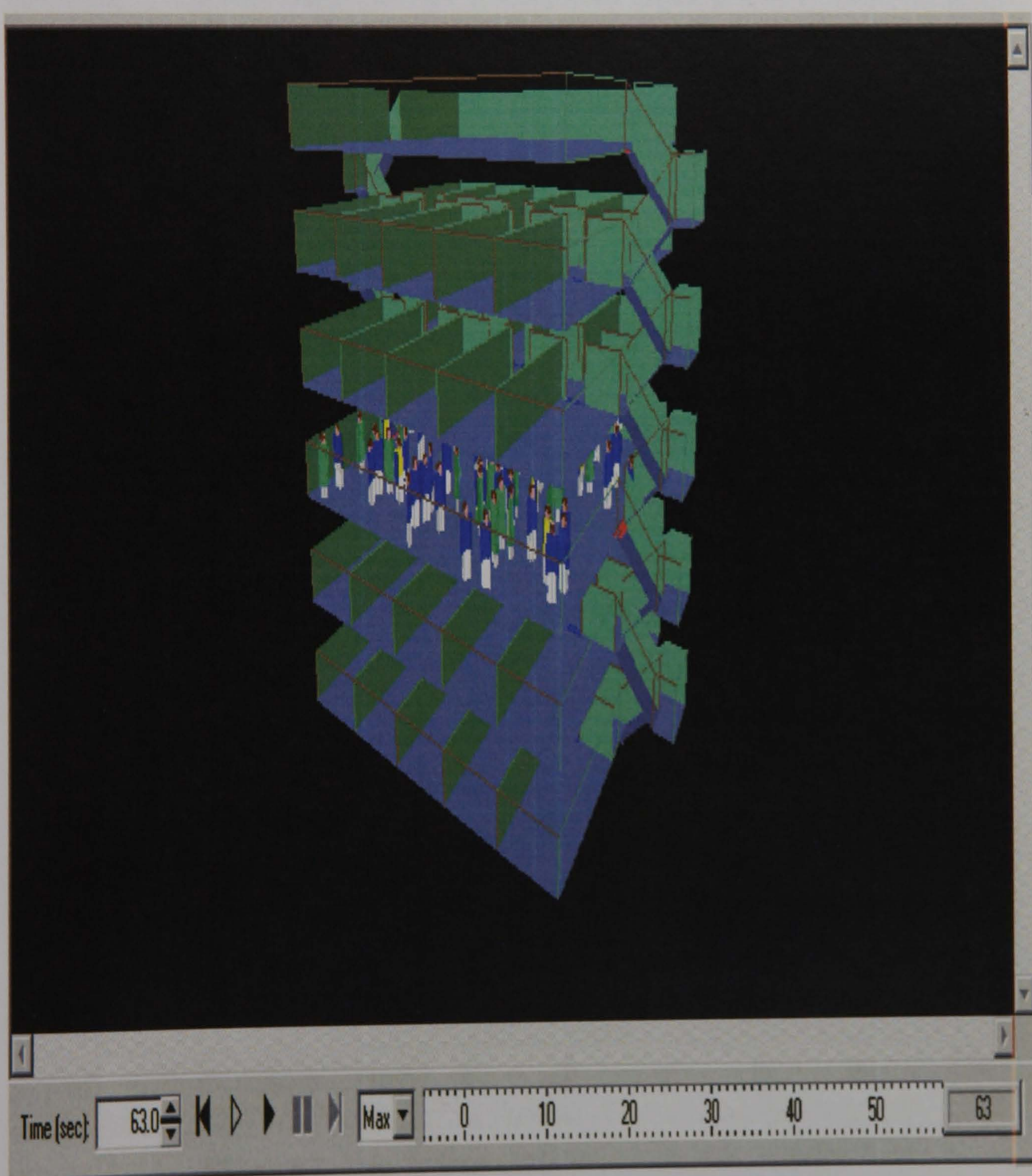


Figure 6.2. Case 1: from cabin to assembly station.

Case 2: From Cabin to Embarkation Station

At the start of the simulation the passengers move from their cabins to the Embarkation station on deck 6 following the shortest route and without stopping at the assembly station. Passenger distribution and uncertainties associated with human behaviour are applied. This case represents a real incident (see Figure 6.3).

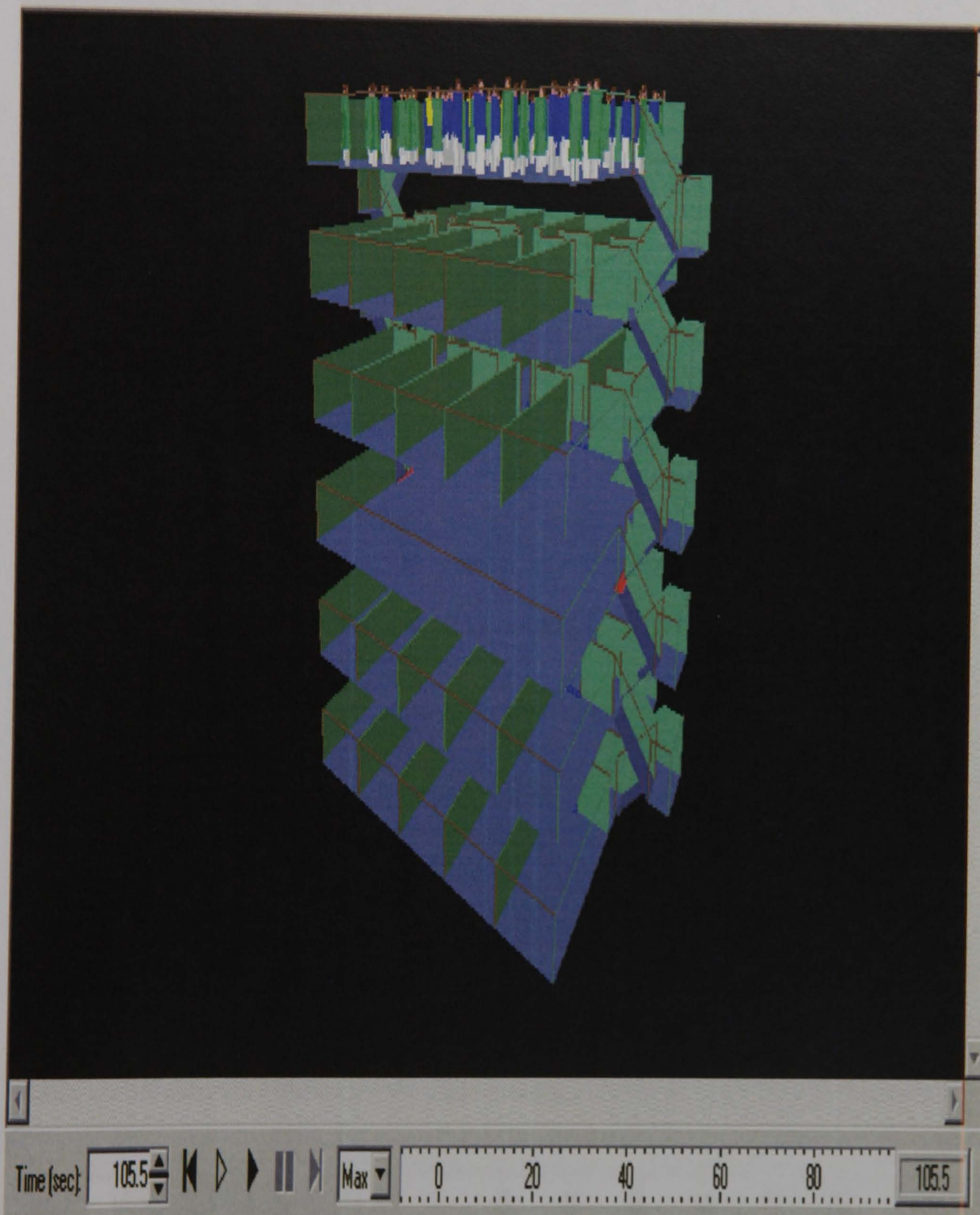


Figure 6.3. Case 2: from cabin to embarkation station.

Case 1 – 1: Blockage of One Fire Door on Assembly Station

The blockage on the evacuation is considering the loss of escape route. When passengers arrive on the deck where there is the assembly station, they still have to queue before arriving at their destination (see Figure 6.4).

Figure 6.4. Case 1 - 1: blockage of one fire door on assembly station.

Case 2 – 1: Blockage of One Staircase on Embarkation Station

The passengers have to travel to reach an alternative stairway that much further than their original choice (see Figure 6.5).

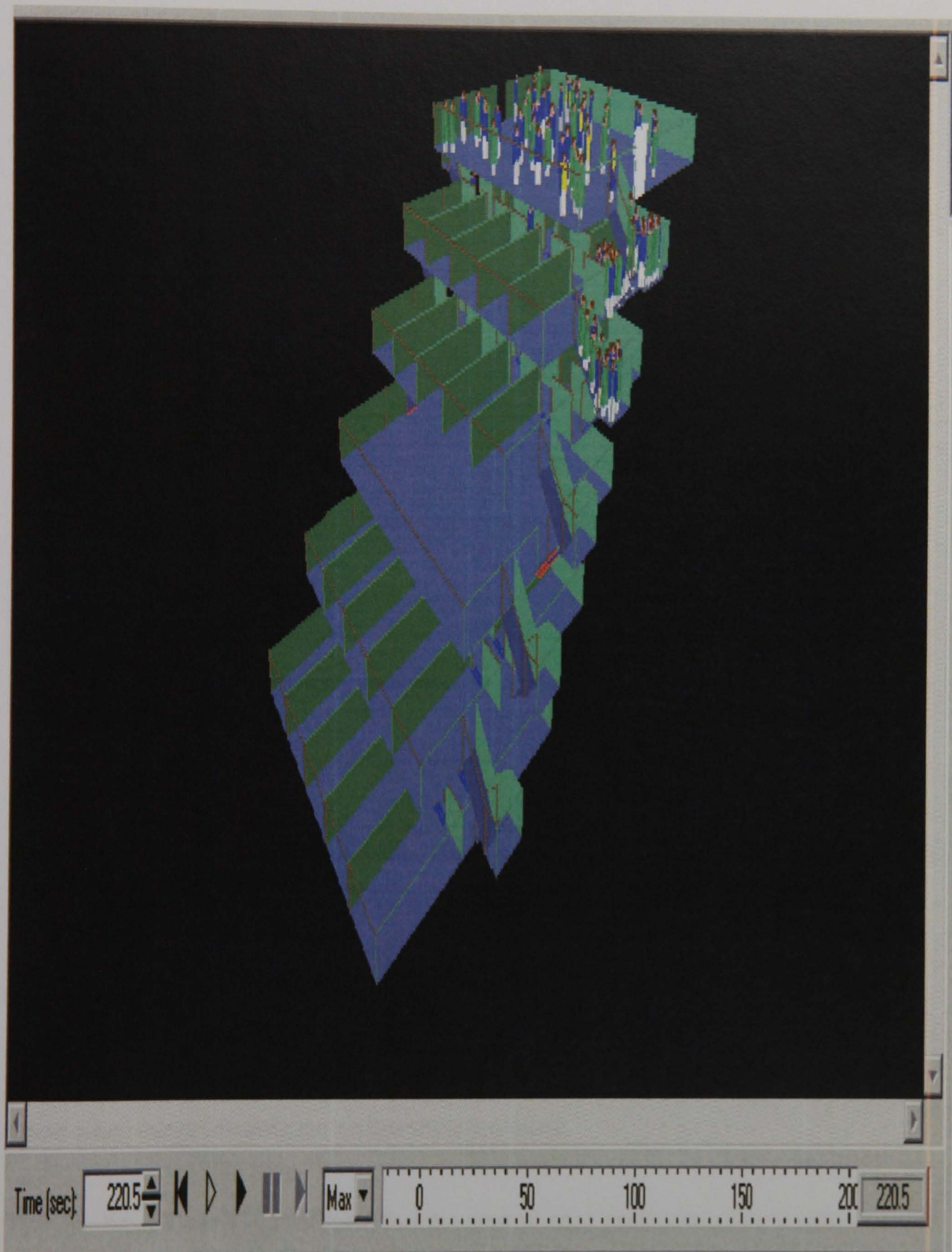


Figure 6.5. Case 2 - 1: blockage of one staircase on embarkation station.

Comments on the results

The results from the case studies presently considered are given in Figure 6.6.

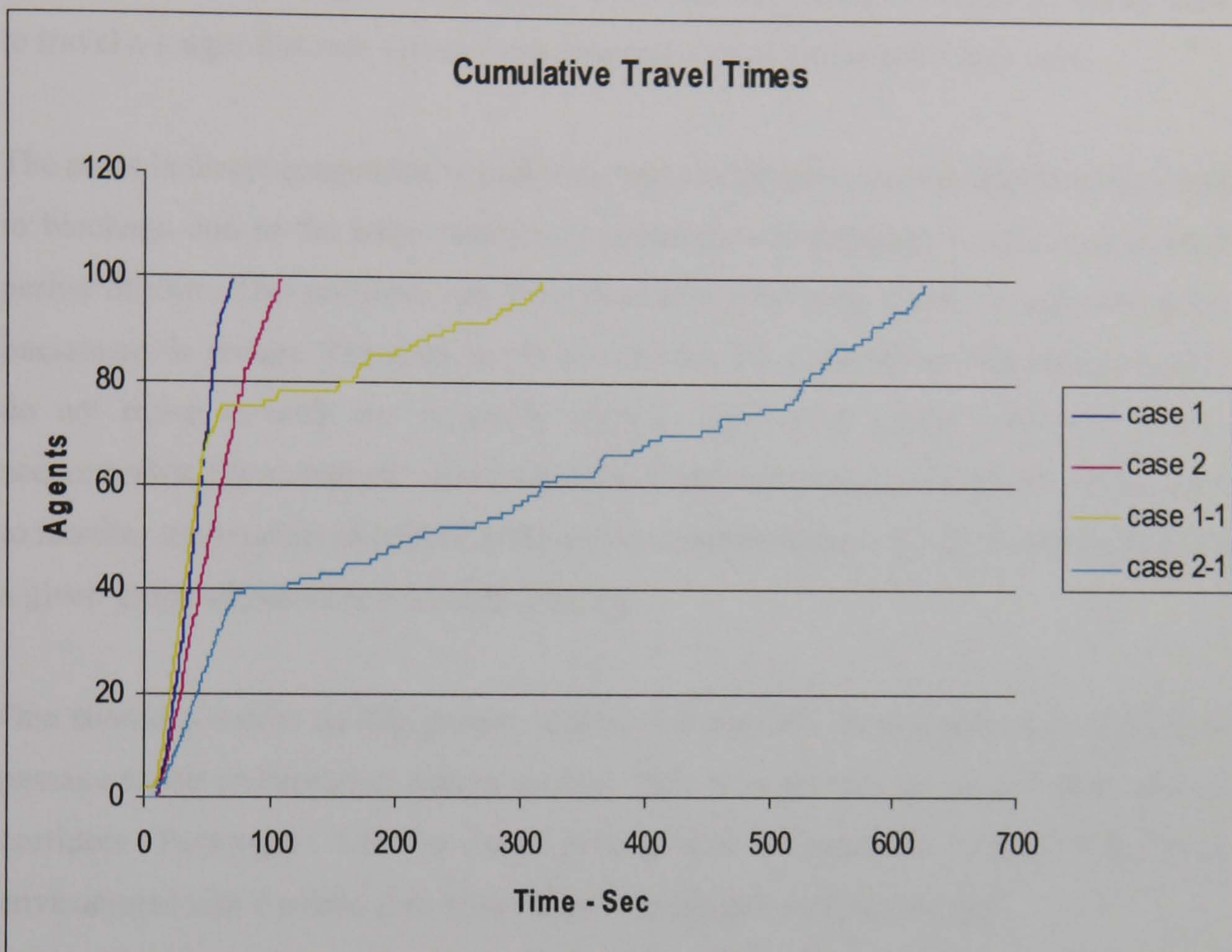


Figure 6.6. Travel time for the cases considered.

Case 1 has the shortest travel time. This is due to the fact that the passengers are simply moving from their cabins to an assembly station. This is illustrated by a steep, 'straight' curve.

Case 2 – here the passengers, rather than going to assembly stations, are instructed to go directly to the embarkation station. Comparing with Case 1, this can be detected by a less steep curve towards the end of the simulation.

The results of **Case 1 – 1** indicate that the start of the simulation curve is similar to the one in Case 1 – despite the fact that a less steep curve towards the middle and end of simulation is detected. The 'bump' on the curve is caused by the fact that on deck 3 assembly station one of the doors was blocked (bottleneck). This means that there is more queuing (compared to Case 1).

Case 2 – 1 has the longest travel time – due to the fact that passengers generally have to travel a longer distance (as they may become lost at the blocked stair exit).

The areas in direct connection to assembly and embarkation station appear to be prone to blockage due to the large number of passengers attempting to enter over a short period of time. This problem may be solved in normal evacuation by assembling the passengers in groups. The crew has to co-ordinate the assembly so that the passengers do not move towards the assembly stations until there exists sufficient area to accommodate the envisaged crowd capacity. Crew members by assembly station have to monitor the number of people there and to communicate to the crew responsible for a given group of passengers to start moving.

One should consider having people waiting for example in assembly area until their passage to the embarkation station is clear. This is to prevent queuing in staircases or corridors. Passengers will be more relaxed and co-operative if they rest in an environment like a public area rather than a small and narrow corridor.

6.5 Conclusion

This chapter has demonstrated the evacuation process on passenger ship within different scenarios. The proposed approach can be used to investigate issues such as blockage exit, passengers and crew movements during emergency situations involving fire. The results of this study have also shown how varies in different evacuation scenarios.

The evacuation analysis by the methodology using computer modelling is a useful tool. It can be used by ship designers during the concept phase, classification societies for the certification of ship design and by ship operators for training both on shore and at sea. In the stages of the design process such analysis will bring important issues of fire safety, evacuation, staffing and procedures to the fore of vessel design in a manner that is reliable, quantifiable and reproducible. In a similar process, classification societies will be able to quickly assess a proposed design, including the crew procedures and determine whether proposed designs meet acceptable standards. Also, operators will be able to assess safety provision on board with respect to number, type and location of passengers, number and location of crew, etc.

References

Galea, E. R. (2000), "Safer by Design: Using Computer Simulation to Predict the Evacuation Performance of Passenger Ships", IMarEST International Conference Safety of Large Passenger Ships – Looking to the Future, Vol 112, Part 2, London, UK, 15–16 May.

Galea, E. R., Filippidis, L., Gwynne, S., Lawrence, P., Sharp, G., Blackshields, D. & Glen, I. (2002), "The Development of an Advanced Ship Evacuation Simulation Software Product and Associated Large Scale Testing Facility for the Collection of Human Shipboard Behaviour Data", RINA Proceedings International Conference on Human Factors in Ship Design and Operation, London, UK, pp 37-50.

Galea, E. R., Lawrence, P., Gwynne, S., Filippidis, L., Blackshields, D., Sharp, G., Hurst, N., Wang, Z. & Ewer, J. (2004), "The Simulation of Ship Evacuation Under Fire Conditions", Proceedings International Conference Fire and Safety at Sea, Melbourne, Australia, 17-19 March.

Glen, I., Igloliorte, G., Galea, E. R. & Gautier, C. (2003), "Experimental Determination of Passenger Behaviour in Ship Evacuations in Support of Advanced Evacuation Simulation", RINA International Conference Passenger Ship Safety, London, UK, 25-26 March.

Gwynne, S., Galea, E. R., Lawrence, P. & Filippidis, L. (2001), "Modelling Occupant Interaction with Fire Conditions Using the Building EXODUS Evacuation Model", Fire Safety Journal, Vol 36, pp 327-357.

IMO (2002), MSC/Circ. 1033, "Interim Guidelines for Evacuation Analyses for New and Existing Passenger Ships", London, UK, 6 June.

Koss, L., Moore, A. & Porteous, B. (1997), "Human Mobility Data for Movement on Ships", RINA International Conference Fire at Sea, London, UK, 20-21 November.

Lopez, A. & Perez, F. (2003), "Designer and Master Aids to Improve the Evacuation of Passenger Ships", SNAME World Maritime Technology Conference, San Francisco, USA.

Majumder, J. (2000), "Behavioural Modelling of Emergency Evacuation from Ro-Ro Passenger/Cruise Ships", Technical Report SSRC-05-00-JM-01-ER, Glasgow, UK, May.

Marine Safety Agency (1996), "Marine Safety Agency Report on 'Exercise INVICTA' held in Dover Harbour; 13 Jan 1996", Southampton, UK, May.

Rodricks, B. & Cooke, P. (1996), "Life Safety Management Systems – Enhancing Passenger Safety", IMarEST Trans, Vol 109, Part 2, pp 117-125.

Rutgersson, O., Tsychkova, E. & Andersson, M. (2003), "Evacuation of Passenger Ships in Rough Weather – A Study of the Behaviour of Equipment and the Interaction with Human Performance", RINA International Conference Passenger Ship Safety, London, UK, 25-26 March.

Shields, T. & Boyce, K. (2000), "A Study of Evacuation from Large Retail Stores", Fire Safety Journal, Vol 35, pp 25-49.

Simões, A., Lam, E., Veitch, B. & Igloliorte, G. (2003), "Quantitative Assessment of Escape and Evacuation", RINA International Conference Passenger Ship Safety, London, UK, 25-26 March.

Soma, H. (2001), "Computer Simulations of Passenger Ship Evacuation", ESREL International Conference Towards a Safer World, Torino, Italy, 16-20 September.

Thompson, T. & Wheatley, N. (2000), "Evacuation of Large Passenger Vessels – Passenger and Crew Drills", IMarEST International Conference Safety of Large Passenger Ships – Looking to the Future, Vol 112, Part 2, London, UK, 15–16 May.

Tsychkova, E. (2000), "Influence of Waves and Ship Motions on Safe Evacuation of Passenger Ships", Licentiate Thesis, Kungliga Tekniska Högskolan (KTH), Sweden, June.

Vassalos, D., Cristiansen, G. & Kim, H. (2001a), "Evi – Passenger Evacuation Performance Assessment in Ship Design and Operation", TIEMS 2001, Oslo, Norway, June.

Vassalos, D., Kim, H. & Cristiansen, G. (2001b), "Passenger Evacuation in a Virtual Ship - Sea Environment and Performance - Based Evaluation", Cruise and Ferry, May.

Vassalos, D., Kim, H., Cristiansen, G. & Majumder, J. (2001c), "A Mesoscopic Model for Passenger Evacuation in a Virtual Ship – Sea Environment and Performance – Based Evaluation", Duisburg, Germany, 4-6 April.

Vassalos, D., Cristiansen, G., Kim, H., Bole, M. & Majumder, J. (2002), "Evacuability of Passenger Ships at Sea", SASMEX, Amsterdam, Netherlands, April.

CHAPTER 7 - FIRE RISK MODELLING OF MACHINERY SPACE: AN APPLICATION OF APPROXIMATE REASONING APPROACH (FUZZY AVERAGING METHOD) IN PASSENGER SHIP ENGINE ROOM

Summary

Fire safety is built up of ignition prevention, early detection of fire, safe personnel evacuation, containment of fire and efficient suppression. In addition, vital machinery functions must be continued during the fire.

This preliminary fire safety study intends to assess the potential hazards that would affect the operation of a ship engine room. The risks associated with such hazards are quantified and ranked in order of priority and assessed for decision-making purposes. This chapter concentrates on the fire risk evaluation of the major hazards threatening the engine room overall rather than focusing on specific areas of the design. The main objective is to propose a framework for modelling system fire safety using an approximate reasoning approach. A case study of the risk to passenger ship engine room due to fire during operation is used to illustrate the application of the proposed risk assessment model.

7.1 Introduction

High fire safety in ships in general and machinery space in particular is a result of correct design and careful crew operations. When either one of these is missing, fire risks are significantly increased.

The available fuel in an engine room of a ship is usually limited to oil, which is stored or used in engines, boilers, lubricants and stores. The tidiness of any engine room will, of course, affect the ease with which a fire may start and develop. Unless an engine room fire becomes serious, it may well be confined to the area in which the outbreak of fire occurred. In the event that an escape of oil does become involved, the probability of fire being communicated to the accommodation is very much higher than fire spread in the reverse direction, because there is a good chance that there will be combustible materials in contact with, or in close proximity to, the accommodation side of the engine room casing. Heat rising from the engine room fire will cause the engine room casing to become hot, which in turn leads to ignition of combustibles by means of heat transfer by conduction or radiation.

The most serious engine room fires therefore occur when an escape of oil becomes ignited. The ease with which oil can be ignited by the introduction of an external source of ignition, depends upon the flash point temperature of that oil. The flash point is the temperature to which the oil must be raised such that a flammable vapour-air mixture will be established at the surface of the liquid.

Heat blister patterns providing clear evidence of oil having burned in the engine room may often be revealed after a fire by using diesel oil to clean soot and dirt deposits from surfaces of machinery and floor plates, etc. [Foster, 1994].

Fires in electrical switchboards and other electrical machinery have the potential to give rise to fire where cable connections and terminations become loose or damaged or where switch or contactor contacts have become eroded. Fires originating in main electrical switchboards seldom develop seriously, because usually only a small amount of cable insulation is exposed within the switchboard area, and for the most part the external portion of the cable is steel wire armoured or metal braided. Spare components are, however, often stored in combustible packaging behind the switchboard and this may extend the fire if it becomes involved [Foster, 1994].

When previous engine room fires are studied, it is apparent that no two fires are identical. All engine rooms are different. Even sister ships have differences. Thus slightly varying details or temporary changes may lead identically ignited fires to totally different end results.

A fire resistant engine room displays lower ignition probability than an average one. A fire resistant engine room remains by definition safer for personnel. This chapter focuses on the fire resistant one. High fire safety and resistance are difficult to achieve when capital and operational costs must be observed. True optimisation cannot be done. Of course the additional costs of improved design can be measured but the probabilistic gain from statistical likelihood of fire and expected damage costs are usually only theoretical figures [Hakkinen, 1997].

In general, ship fires have been widely investigated. Single fires are analysed (with varying accuracy) and reported to International Maritime Organization (IMO) related committee. Both the IMO and classification societies issue statistics and summaries of the fire reports. Increasing attention is also given today to the incidents and near miss cases that could have lead to disastrous consequences. Some of the fire reports issued by national safety authorities are really valuable materials for the fire safety researcher.

Fortunately ship fires seldom result in catastrophes. Often the losses are mainly economical with minor personnel injuries. However some 100 to 200 fires are reported annually. Those fires involve human losses, significant ship damages or traffic interruption. Among these fires a third were initiated in engine rooms.

Engine room fire safety has been considered by many parallel methods. IMO and other authorities have guided the technical development by detailed regulations on ship structures and equipment. Many rules and guidelines apply to the machinery systems and machinery spaces [IMO, 1997].

7.2 Fire Safety of Ship Engine Room

7.2.1 Criteria for fire safety

In principle, general fire safety is presented by the following sequential criteria:

1. Fire ignition must be prevented.

2. However, if fire is ignited, alarm or other suitable indications must be triggered without delay.

3. The indications must raise further action, like extinguishing, equipment shut down, etc.

4. Fire suppression must be rapid, efficient and appropriate.

5. Personnel must be safely evacuated from the danger zone.

6. Fire must be confined in the compartment of ignition and not spread out to other zones.

IMO and classification societies specify measures required to fulfil these criteria in principle. Extensive experimental and theoretical research lies behind the regulations and experience from the accidents is utilised. Yet regrettably engine room fires occur, which are not fully controlled according to items 1 to 6 above.

Significant development work has been performed among the fire detection and extinguishing equipment manufacturers. Some of them are complaining that conservative regulations and acceptance tests are hindering the progress [Hakkinen, 1997]. However, this particular topic is not further discussed in this chapter.

'Normal conditions' refer commonly to cases when fire has been ignited by an accidental mechanical failure or a technical cause. A frequently quoted example is the crank case explosion of a medium speed diesel engine. In some cases the damage included heavy drive gear parts breaking through the engine frame, hitting equipment containing flammable oil and causing oil ignition. While such fires are commonly regarded as totally unexpected, closer inspection may reveal that primary causes included errors in engine design, prolonged operation on worn-out piston rings and/or engine overload. Causes are widely different and they often occur simultaneously.

'Abnormal conditions' refer to circumstances where an unexpected and inherent incident causes engine errors. Typical examples are temporary stowing of combustible materials in a high fire risk area, leaving the exhaust gas manifold thermal insulation uninstalled "only for the short coffee break", piping design where ruptures are generated but they remain unnoticed, etc. [Hakkinen, 1997].

7.2.2 Fire safety

Fire safety can be defined and quantified in many ways. Statistical evaluation of fire safety is usually derived from a number of reported fires. This data can be used to calculate ignition probabilities with respect to figures for specified machinery spaces, ships of certain age, various flags and categories. Yet this evaluation tool has some drawbacks. Near miss-cases are ignored although they could produce valuable information for producing fire risk control measures. Experience confirms that various incidents are many times more frequent than actual fires. Furthermore some two thirds of ignited fires are instantly suppressed and remain unreported.

Most of the statistical data contains very little information about the primary cause of fire origin. Valuable information on spread-out and damages is sometimes given in separate fire reports but summaries of such information are rare.

The number of casualties and extent of damages are given in statistics to describe how serious the engine room fires typically are. These figures give unfortunately only limited help for the design and operational aspects of improved fire resistance.

Profound analysis of single fire cases and their reports has appeared to be very valuable. The fire has to be investigated as a process starting long before the ignition and ending after the completion of investigation and damage repair [Hakkinen, 1997].

7.2.3 Scope of research

In this chapter, the main attention was given to ships with diesel propulsion and mechanical and electrical power transmission. Besides the propulsion machinery was electric and thermal energy generation with their auxiliaries included. The investigated ship systems included steering gear, fire and bilge piping systems. The selected steel structures in machinery spaces were evaluated.

Other propulsion machinery concepts were not included in this chapter. Gas turbines have inherently good fire safety record, mainly due to the protective modular casing and the simplified fuel system. In many respects the auxiliary machinery in turbine driven ships has equivalent or better fire safety than diesel driven ships.

7.3 Investigation of Previous Accidents Relative to Engine Room Fire

This investigation comprises survey reports on 73 NK-classed ships involving engine room fires during the period from 1980 to 1992 [NKK, 1994]. Ships damaged by small fires or suffered sinking without being reported to the NK society are excluded from this investigation. Internal fires or explosions in boilers, exhaust gas economisers, waste oil incinerators, turbo-charges, crankcases, etc., without the fire extending to the engine room were considered as fire damage to the machinery itself, therefore, they are excluded from this investigation. Fire damage to the hull following an engine room fire was considered and counted as an engine room fire and a fire caused by rocket or missile attacks during a war was considered to be a fire in hull compartments.

7.3.1 Results of investigation

The results of the investigation are summarised as follows [NKK, 1994]:

1. 73 ships were damaged by engine room fires during the period from 1980 to 1992.

2. About six ships per year were damaged by engine room fires, which are 0.1% of all 6,000 NK classed ships. As a comparison, about seven ships per year were damaged by fire in hull compartments.

3. Engine room fires often occurred when ships were underway, which accounted for about 75% of the total number of ships damaged by engine room fires. 52% of ships with engine room fires when underway became unnavigable.

4. The main cause of fire resulting in an unnavigable condition is a main electric source failure caused by the main switchboard or the main electric cables under the ceiling burning due to the ignition of a spray of fuel oil or lubricating oil.

5. On average, one crew member per year was killed and one crew member was injured or suffocated from carbon monoxide per year due to fires. Engine room fires are mainly caused by flammable oil igniting and there are many cases of human casualties due to evacuations delays from engine rooms where fire and smoke had spread quickly.

6. Fire often occurred in daytime during maintenance work by the crew. There were many fires caused by human error due to misoperation or overhauling of machinery, incorrect repair, etc. Alternatively, it was found that in unmanned ships, fires often occurred not only during daytime, but also early in the morning.

7. There are no particular correlations between the number of fires and a ship's age and gross tonnage.

8. Fires often occurred on reefer ships and car carriers having small engine rooms.

9. The fuel oil piping of main engines and generator engines and the main switchboard are the main sources of fire followed by fuel oil piping of the boiler.

10. Fires at the fuel oil piping of main engines and generator engines are caused by fuel oil spraying due to loose or broken fittings on fuel oil piping caused by vibration. The main cause of fire on fuel oil piping of generator engines is fuel oil spraying due to broken fittings on the fuel valve cooling oil piping.

11. Fires on lubricating oil piping account for 25% of fires on fuel oil piping.

12. No cases of engine room fire caused by a soot fire in an exhaust gas economizer were reported.

13. The number of machinery fires was twice as many as that of electric equipment fires.

14. No engine room fire extending to hull compartments was reported for ships having keels laid after 1st September, 1984. This may be because the 81'SOLAS Amendment was adopted and the regulations on fire protection for hull and electric cables were introduced from that date.

15. The percentages of fire casualties between M0 (M0-ships are those provided with alarm systems in accordance with the requirement of the "Rules for Automatic and Remote Control Systems") and Non-M0 ships are almost the same. However, the percentage of fires detected by a fixed detector fire alarm was 50% in M0 ships and only 19% in Non-M0 ships, because the installation of fixed fire detection systems was not required for Non-M0 ships having keels laid before 1st September, 1984, in accordance with the 81'SOLAS Amendment.

16. There were fires caused by improper installation of machinery, exhaust gas pipes and electric cables. The engine room arrangement should be considered in a "Fire Risk Analysis" [NKK, 1994].

7.3.2 Locations in the engine room with a high fire risk

Figure 7.1 shows the identified locations in an engine room taken from data on fires that have occurred in 73 ships classed with NK from 1980-1992 [NKK, 1994].

Fires did not occur uniformly at all the locations in the engine room space. Fires in the engine room were concentrated in areas where flammable oils are liable to leak easily, and in the vicinity of an ignition source such as a high-temperature surface or where there is electric equipment liable to generate sparks or overheating. Fuel oil pipes fitted to main engines, or generator engines, burner fuel injection pipes in boilers, exhaust gas pipes, turbochargers, and main switchboards are locations with a high fire risk. Countermeasures for preventing fires must be adopted on a top-priority basis at such high fire risk areas.

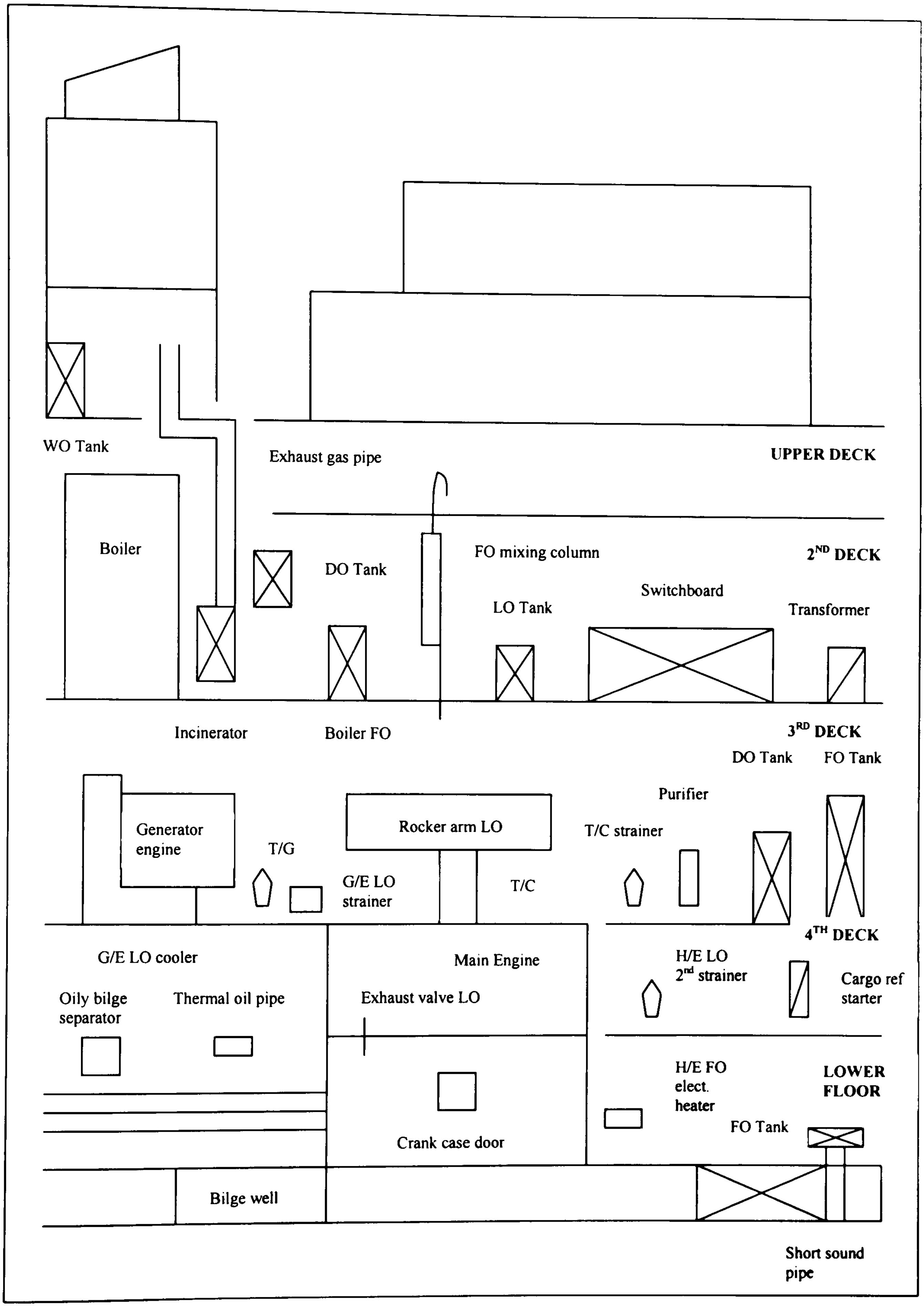


Figure 7.1. Sources of fire in engine room [NKK, 1994].

7.3.3 Sources of ignition

The sources of ignition are shown as follows [NKK, 1994]:

- Fuel Oil (FO): 30 ships
  - Main Engine (M/E) FO piping: 8
  - Generator Engine (G/E) FO piping: 8
  - Boiler FO piping: 6
  - FO tank: 3
  - FO tank short sounding pipe: 2
  - FO spray after G/E damage: 2
  - Diesel oil purifier: 1

- Leakage Oil (LO): 8 ships
  - M/E LO piping: 2
  - G/E LO piping: 1
  - LO tank: 1
  - LO strainer: 3
  - M/E crankcase explosion: 1

- M/E Turbo Charger (T/C) explosion: 5 ships

- Waste Oil (WO): 2 ships
  - WO tank: 1
  - Incinerator: 1

- Electrical Equipment: 18 ships
  - Main switchboard: 8
  - Starter: 4
  - Control panel: 1
  - Generator: 2
  - Motor: 1
  - Transformer: 1

- FO electric heater: 1

- Others: 10 ships
  - Repair at shipyard, loading: 7
  - Unknown: 3

7.3.4 Breakdown of causes of fires

The number of ships in each category is presented within ( ) [NKK, 1994].

- FO (30)
  - M/E FO piping (8)
    - Disconnection of drain valve in FO supply piping (1)
    - Breakage of air relief valve in FO supply piping (1)
    - Breakage of cock in FO return piping (1)
    - Disconnection of vinyl hose in FO return piping (1)
    - Crack in welding seam in FO pipe connection (1)
    - Breakage of fitting bolts between FO inlet pipe and FO injection pump (2)
    - FO leakage from FO electric sheath heater due to mis-fitting (1)
  - G/E FO piping (8)
    - Loosening of FO supply piping (1)
    - Breakage of FO pressure gauge pipe in FO supply piping (1)
    - Breakage of FO valve cooling oil pipe (3)
    - Breakage of FO valve cooling oil pipe in way of brazing fitting (1)
    - Breakage of differential pressure gauge pipe for FO strainer due to explosion of air inlet pipe (1)
    - Loosening of FO injection pump flange (1)
  - Boiler FO piping (6)
    - Burner mal-function (5)
    - Loosening and disconnection of threaded pipe connection in diesel oil supply piping (1)
  - FO tank (3)
    - Breakage of glass level gauge (1)

- Diesel oil overflow from air vent pipe of FO service tank for boiler (1)
- FO tank short sounding pipe (1)
  - Ignition of FO vapour during bunkering (1)
- G/E damage (2)
  - FO spraying due to damage of G/E connecting rod (2)
- Diesel oil purifier (1)
  - FO spraying due to improper assembling of diesel oil purifier (1)

- LO (8)
  - M/E LO piping (3)
    - Loosening and disconnection of LO supply pipe for exhaust valve driving gear (1)
    - Disconnection of LO supply pipe for exhaust valve push rod and rocker arm (1)
    - M/E crankcase explosion (1)
  - M/E LO strainer (1)
    - Loosening of LO 2nd strainer cover (1)
  - G/E LO piping (1)
    - Loosening of thermometer fitting of LO cooler (1)
  - LO tanking for T/C of M/E (1)
    - LO overflow from LO storage tank (1)
  - Strainer for T/C of M/E (1)
    - Loosening of bolts for packing cover (1)
  - LO strainer for G/E (1)
    - LO spraying from air relief valve during cleaning (1)

- Waste Oil (2)
  - Waste oil sprayed from the disconnected fitting cover of waste oil tank float gauge (1)
  - Soot fire in incinerator (1)

- Electrical Equipment (18)
  - Main switchboard (8)
    - Arc from air circuit breakers (2)

- Short-circuit of non-fused breaker caused by overheating (1)
- Short-circuit of non-fused breaker for shore connection caused by overheating (1)
- Degradation of terminal for Turbo/Generator (1)
- Unknown (2)

- Starter Panels (4)
  - Short-circuit of internal wiring in starter panel for LO pump (1)
  - Short-circuit in starter panel for FO purifier (1)
  - Chattering of magnetic contactor in starter panel for refrigerating machine and air compressor (1)
  - Short-circuit in control panel for refrigerating machine (1)
- Generator (2)
  - Short-circuit at cable terminal of generator (2)
- Motor (1)
  - Overheating of motor for main cooling sea water pump (1)
- Transformer (1)
  - Overheating of transformer (1)
- Electric heater (1)
  - Incorrect fitment of electric heater for FO service tank (1)

- Others (12)
  - T/C of M/E (5)
    - Explosion of T/C of M/E (5)
  - Mooring and repair work at shipyard (7)
    - Spark from welding (2)
    - Spark from gas cutting (4)
    - Explosion during cargo loading of Naphtha (1)

- Unknown (3)
  - Sinking (1)
  - No report (2)

7.4 Approximate Reasoning Approach

7.4.1 Approximate reasoning approach

7.4.1.1 Membership functions

The main artificial intelligence mechanism behind a typical fuzzy safety model is its fuzzy inference engine. A fuzzy inference engine comprises the selection or development of the type/types of fuzzy membership function used to represent risk levels and fuzzy rule bases to generate fuzzy safety estimates. The linguistic variables are employed in the development of fuzzy membership function for each input parameter. The goal of fuzzy linguistic variables is to represent the condition of an attribute/parameter at a given interval. The four attributes/parameters (input variables) considered in this study are ***failure rate, consequence severity, failure consequence probability*** of a cause to a technical failure, and ***control measure*** incorporated in the design or operation.

The four fundamental parameters ***failure rate, consequence severity, failure consequence probability*** and ***control mechanism*** are represented by natural languages, which can be further described by different types of membership function. A membership function is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between *0* and *1*. Four different types of membership function are used in this study. The simplest membership functions are formed using straight lines. These straight-line membership functions have the advantage of simplicity. All of these memberships are commonly used to describe risks in safety assessment [Wang & Ruxton, 1997] [Sii, 2000] [Sii & Wang, 2000] [Sii, et al., 2001a-b]. The fuzzy membership functions are generated utilising the linguistic categories identified in the knowledge acquisition and consisting of a set of overlapping curves.

Knowledge acquisition, development of fuzzy linguistic variables, development of membership functions and Analytic Hierarchy Processing (AHP) analysis are usually required to construct the linguistic safety levels and associated fuzzy membership functions [Klir & Yuan, 1995]. In knowledge acquisition, data collection analysis, expert and engineering judgements, fuzzy modelling and concept mapping are performed sequentially to classify the knowledge. The goal is to establish linguistic variables based on fuzzy set theory, for qualifying and quantifying the ***safety estimates*** to develop fuzzy membership functions for representing risks. The arbitrariness and variability associated with combining information from various data and knowledge acquisition channels are the basis for utilising the approximate reasoning approach in the decision making process. The approximate reasoning analysis using fuzzy logic systems does perform such transformation and combination of information from different sources [Wang L. X., 1997].

This section defines the following forms of membership function as perceived by experts for risk analysis in this chapter:

- A single deterministic value with 100 % certainty (Figure 7.2 (a)).
- A closed interval defined by an equally likely range (Figure 7.2 (b)).
- A triangular distribution defined by a most likely value, with lower and upper least likely values (Figure 7.2 (c)).
- A trapezoidal distribution defined by a most likely range, with lower and upper least likely values (Figure 7.2 (d)).

Each type of membership function is described in detail as follows:

7.4.1.1.1 A single deterministic value

A single deterministic membership function is defined by a crisp parameter *[a]*, in this case the interval on x-axis is between *0* and *10*.

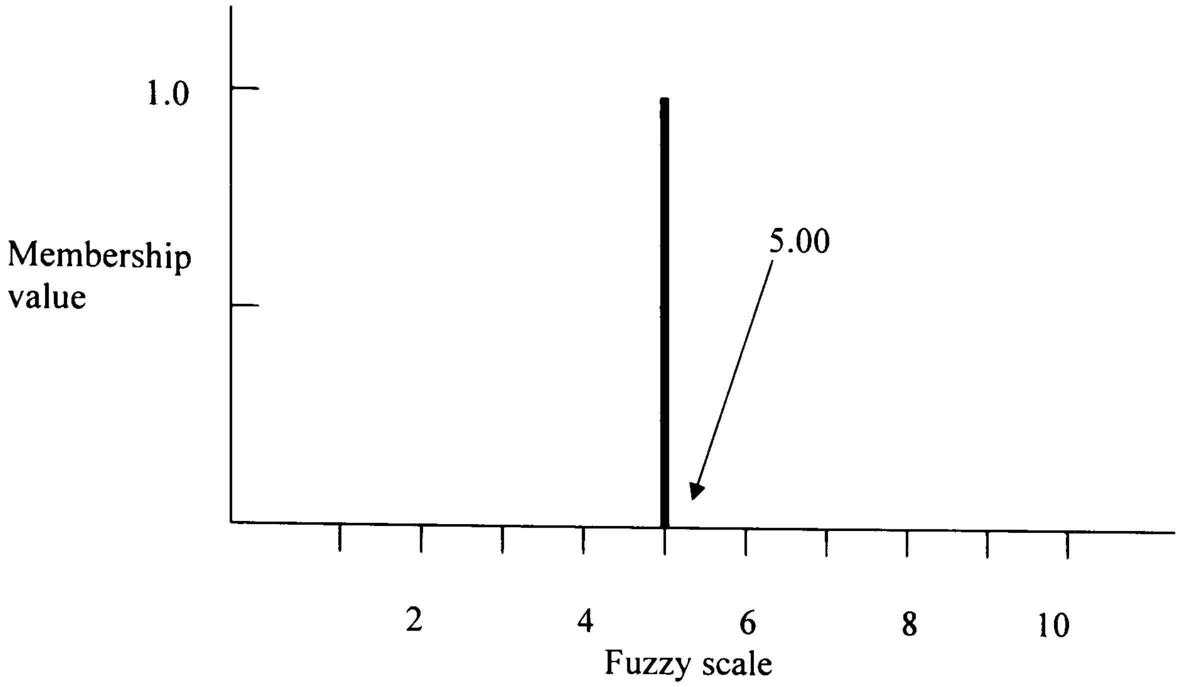


Figure 7.2 (a). A single deterministic value of 5.0 with 100 % certainty.

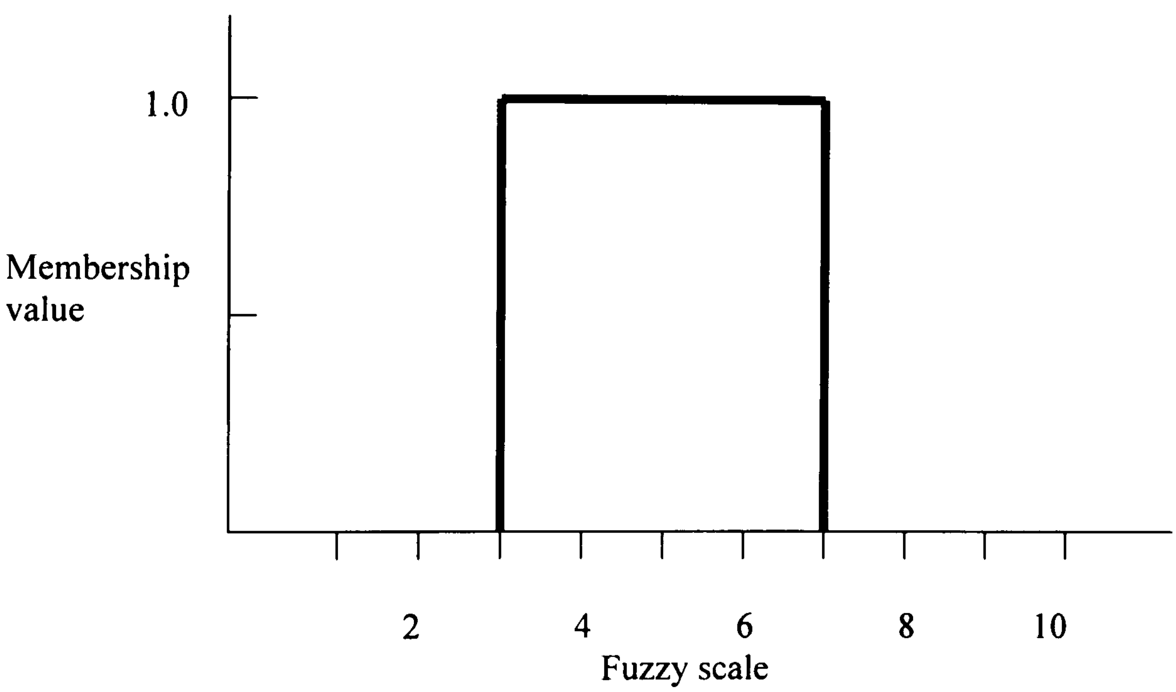


Figure 7.2 (b). A closed interval defined by an equally likely range between 3.0 and 7.0.

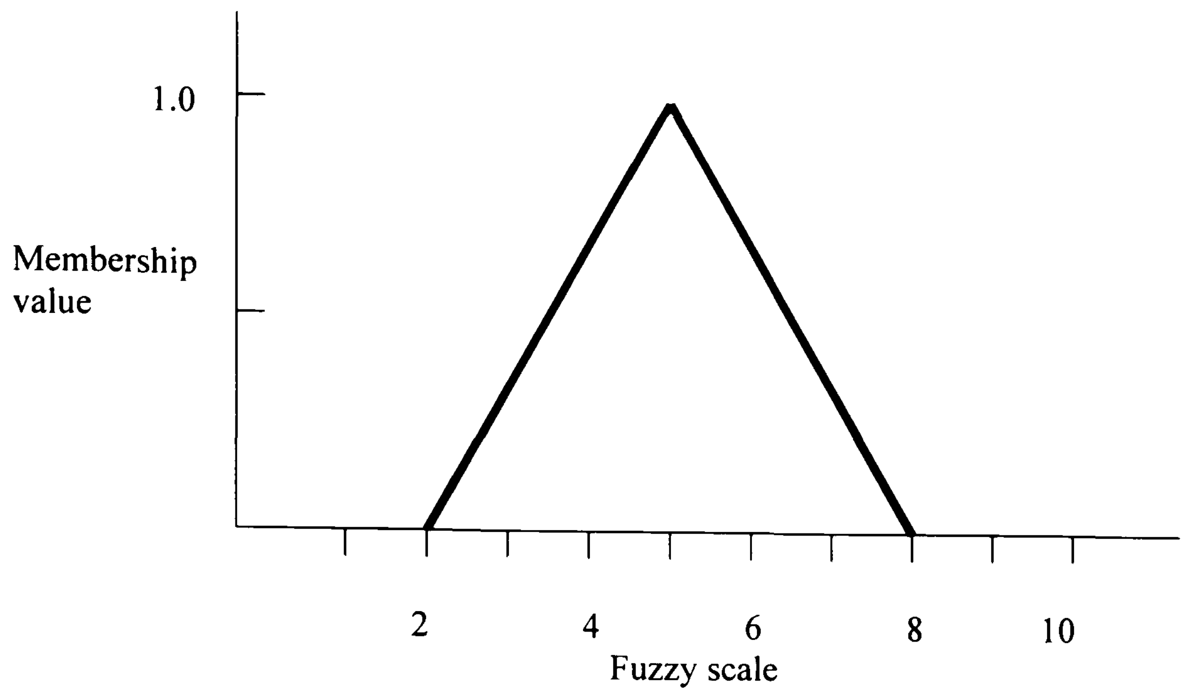


Figure 7.2 (c). A triangular distribution defined by a most likely value of 5.0, with a lower least likely value of 2.0 and an upper least likely value of 8.0.

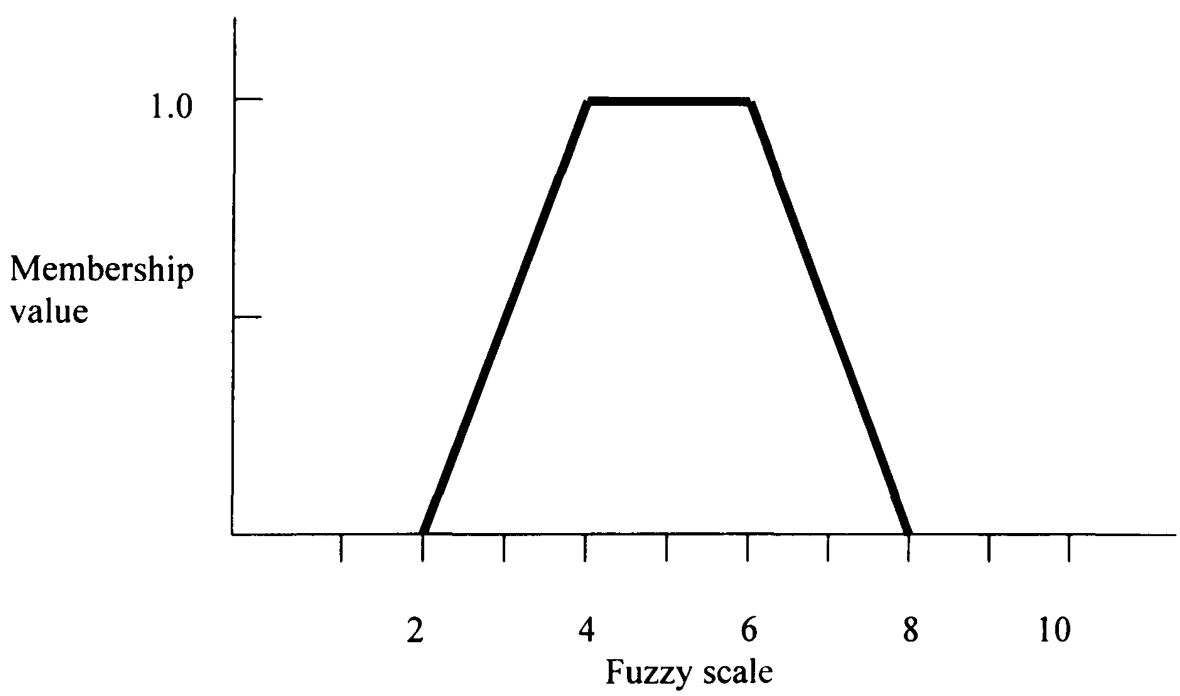


Figure 7.2 (d). A trapezoidal distribution defined by a most likely range between 4.0 and 6.0, with a lower least likely value of 2.0 and an upper least likely value of 8.0.

7.4.1.1.2 A closed interval

A closed interval membership function is represented in the form of *[a, a, b, b]*, where the first *a* is the membership function's left intercept with grade equal to *0*, the second *b* is the membership function's right intercept with grade equal to *0*, and the second *a* and first *b* are the membership function's left and right intercepts at grade equal to *1*. The function *y = closed interval (x, [a, a, b, b])* is written to return the membership values corresponding to the defined universe of discourse *x*. The parameters that define the closed interval membership function *[a, a, b, b]* must be in the discretely defined universe of discourse.

7.4.1.1.3 Triangular membership function

A triangular membership function is normally defined by *[a, b, c]*, where *a* is the membership function's left intercept with grade equal to *0*, *b* is the centre peak where the grade equals to *1* and *c* is the right intercept at grade equal to *0*. The function *y = triangle (x, [a, b, c])* is written to return the membership values corresponding to the defined universe of discourse *x*. The parameters that define the closed interval membership function *[a, b, c]* must be in the discretely defined universe of discourse.

7.4.1.1.4 Trapezoidal membership function

A trapezoidal membership function is defined by *[a, b, c, d]*, where *a* is the membership function's left intercept with grade equal to *0*, *b* is the membership function's left intercept with grade equal to *1*, *c* is the membership function's right intercept with grade equal to *1*, and *d* is the membership function's right intercept with grade equal to *0*. The function *y = trapezoidal (x, [a, b, c, d])*, is written to return the membership values corresponding to the defined universe of discourse *x*. The parameters that define the closed interval membership function *[a, b, c, d]* must be in the discretely defined universe of discourse.

7.4.2 Background of fuzzy averaging for safety assessment

Safety assessment provides the basic safety related information for any new project or engineering product at the initial design stages. The ability to identify, assess and evaluate anticipated hazards requires the study of imprecise data information coming from a rapidly changing environment, a task for which fuzzy logic may be better suited to deal with than classical methods. Analysis of complex situations needs the efforts and opinions of many experts. The experts' opinions, almost never identical, are either more or less close or alternatively more or less conflicting. They have to be combined or aggregated in a rational way in order to produce one conclusion. In this chapter the methodology of fuzzy averaging is introduced. It is also applied to fire risk modelling.

7.4.2.1 Statistical average

One of the most important contributions of statistics in applications lies in its concepts in the *average* or *mean* of *n* measurements, readings, or estimates expressed by real numbers $r_1,....,r_n$. It is defined by:

$$r_{ave} = \frac{r_1 + ... + r_n}{n} = \frac{\sum_{i=1}^{n} r_i}{n} \quad (1)$$

The above measurements are considered to be of equal importance. The *mean* or *average* which is typical or representative of *n* measurements is known as a measure of central tendency.

If the measurements have various degree of importance, then the concept of *weighted average* or *weighted mean* is introduced. The weights reflect the relative importance or strength of the measurements. The concept of *average* (normally called as *crisp average*) can be generalized by substituting fuzzy numbers for the real numbers in Equation (1). The generalization process normally requires complicated computations involving complex arithmetic operations with fuzzy numbers. Since the main objective of this study is to explore the potential of fuzzy logic concept in safety assessment and safety based decision support, the generalization procedure is restricted to triangular and trapezoidal numbers. They are used very often in applications and besides, it is easy to perform arithmetic operations with them. This is demonstrated in a case study in the ensuing section.

7.4.2.2 Arithmetic operations with fuzzy triangular and trapezoidal numbers

7.4.2.2.1 Addition of fuzzy triangular numbers

It can be proved that the sum of two triangular numbers $A_1 = \left(a_1^{(1)}, a_M^{(1)}, a_2^{(1)}\right)$ and $A_2 = \left(a_1^{(2)}, a_M^{(2)}, a_2^{(2)}\right)$, is also a triangular number, i.e.,

$$A_1 + A_2 = \left(a_1^{(1)}, a_M^{(1)}, a_2^{(1)}\right) + \left(a_1^{(2)}, a_M^{(2)}, a_2^{(2)}\right) = \left(a_1^{(1)} + a_1^{(2)}, a_M^{(1)} + a_M^{(2)}, a_2^{(1)} + a_2^{(2)}\right) \tag{2}$$

This summation formula can be extended for *n* triangular numbers and also it can be applied for both left and right values in a triangular number.

7.4.2.2.2 Multiplication of a fuzzy triangular number by a real number

The product of a fuzzy triangular number *A* with a real number *r* is also a triangular number, i.e.,

$$Ar = rA = r(a_1, a_M, a_2) = (ra_1, ra_M, ra_2) \tag{3}$$

7.4.2.2.3 Division of a fuzzy triangular number by a real number

This operation is defined as multiplication of *A* by *1/r* provided that *r* is not *0*. Hence Equation (3) gives:

$$\frac{A}{r} = \frac{1}{r}(a_1, a_M, a_2) = \left(\frac{a_1}{r}, \frac{a_M}{r}, \frac{a_2}{r}\right) \tag{4}$$

Operations with trapezoidal numbers can be performed similarly to those with triangular numbers.

7.4.2.2.4 Addition of fuzzy trapezoidal numbers

The sum of trapezoidal numbers $A_1 = \left(a_1^{(1)}, b_1^{(1)}, b_2^{(1)}, a_2^{(1)}\right)$ and $A_2 = \left(a_1^{(2)}, b_1^{(2)}, b_2^{(2)}, a_2^{(2)}\right)$ is also a trapezoidal number, i.e.,

$$A_1 + A_2 = \left(a_1^{(1)}, b_1^{(1)}, b_2^{(1)}, a_2^{(1)}\right) + \left(a_1^{(2)}, b_1^{(2)}, b_2^{(2)}, a_2^{(2)}\right) = \left(a_1^{(1)} + a_1^{(2)}, b_1^{(1)} + b_1^{(2)}, b_2^{(1)} + b_2^{(2)}, a_2^{(1)} + a_2^{(2)}\right) \quad (5)$$

Equation (5) can be generalized for n trapezoidal numbers.

7.4.2.2.5 Multiplication of a fuzzy trapezoidal number by a real number

The general operation involved in multiplication of a fuzzy trapezoidal number A by a real number r is shown in Equation (6) as follows:

$$Ar = rA = \left(ra_1, rb_1, rb_2, ra_2\right) \quad (6)$$

7.4.2.2.6 Division of a fuzzy trapezoidal number by a real number

The general operation involved in division of a fuzzy trapezoidal number A by a real number r is shown in Equation (7) as follows:

$$\frac{A}{r} = \frac{1}{r}A = \left(\frac{a_1}{r}, \frac{b_1}{r}, \frac{b_2}{r}, \frac{a_2}{r}\right), \quad r \neq 0 \quad (7)$$

7.4.2.2.7 Sum of fuzzy triangular and trapezoidal numbers

Consider fuzzy triangular number $A_1 = \left(a_1^{(1)}, a_M^{(1)}, a_2^{(1)}\right)$ which can be presented as a fuzzy trapezoidal number in the form of $\left(a_1^{(1)}, a_M^{(1)}, a_M^{(1)}, a_2^{(1)}\right)$ and trapezoidal number $A_2 = \left(a_1^{(2)}, b_1^{(2)}, b_2^{(2)}, a_2^{(2)}\right)$. Applying Equation (5) gives Equation (8), which is a natural extension of Equation (5).

$$A_1 + A_2 = \left(a_1^{(1)}, a_M^{(1)}, a_M^{(1)}, a_2^{(1)}\right) + \left(a_1^{(2)}, b_1^{(2)}, b_2^{(2)}, a_2^{(2)}\right) = \left(a_1^{(1)} + a_1^{(2)}, a_M^{(1)} + b_1^{(2)}, a_M^{(1)} + b_2^{(2)}, a_2^{(1)} + a_2^{(2)}\right) \quad (8)$$

7.4.2.3 Fuzzy Averaging

7.4.2.3.1 Triangular average formula

Consider n triangular numbers $A_i = \left(a_1^{(i)}, a_M^{(i)}, a_2^{(i)}\right)$, $i = 1, ..., n$. Fuzzy averaging of triangular numbers can be performed by two steps. First, addition operation is used to sum up the total triangular numbers and then division operation by a real number (the total number of triangular numbers under study) to give the triangular average (mean) A_{ave}, which is a triangular number.

$$A_{ave} = \frac{A_1 + ... + A_n}{n} = \frac{\left(a_1^{(1)}, a_M^{(1)}, a_2^{(1)}\right) + ... + \left(a_1^{(n)}, a_M^{(n)}, a_2^{n}\right)}{n}$$
$$= \frac{\left(\sum_{i=1}^{n} a_1^{i}, \sum_{i=1}^{n} a_M^{(i)}, \sum_{i=1}^{n} a_2^{(i)}\right)}{n}.$$

The general operation is shown in Equation (9).

$$A_{ave} = \left(m_1, m_M, m_2\right) = \left(\frac{1}{n}\sum_{i=1}^{n} a_1^{(i)}, \frac{1}{n}\sum_{i=1}^{n} a_M^{(i)}, \frac{1}{n}\sum_{i=1}^{n} a_2^{(i)}\right) \quad (9)$$

7.4.2.3.2 Weighted triangular average formula

If each real numbers λ_i represents the degree of importance of $A_i = \left(a_1^{(i)}, a_M^{(i)}, a_2^{(i)}\right)$, $i = 1, ..., n$, then the weighted triangular average (mean) A_{ave}^{w} is obtained as follows:

$$A_{ave}^{w} = \frac{\lambda_1 A_1 + ... + \lambda_n A_n}{\lambda_1 + ... + \lambda_n}$$
$$= \omega_1\left(a_1^{(1)}, a_M^{(1)}, a_2^{(1)}\right) + ... + \omega_n\left(a_1^{(n)}, a_M^{(n)}, a_2^{(n)}\right)$$

$$= \left(\omega_1 a_1^{(1)}, \omega_1 a_M^{(1)}, \omega_1 a_2^{(1)}\right) + \ldots + \left(\omega_n a_1^{(n)}, \omega_n a_M^{(n)}, \omega_n a_2^{(n)}\right)$$

$$= \left(\omega_1 a_1^{(1)} + \ldots + \omega_n a_1^{(n)}, \omega_1 a_M^{(1)} + \ldots + \omega_n a_M^{(n)}, \omega_1 a_2^{(1)} + \ldots + \omega_n a_2^{(n)}\right)$$

Where $\omega_i = \dfrac{\lambda i}{\sum_{j=1}^{n} \lambda j}$ $(j = 1, \ldots, n)$

The generalized equation is shown as follows:

$$A_{ave}^{w} = \left(m_1^{w}, m_M^{w}, m_2^{w}\right) = \left(\sum_{i=1}^{n} \omega_i a_1^{(i)}, \sum_{i=1}^{n} \omega_i a_M^{(i)}, \sum_{i=1}^{n} \omega_i a_2^{(i)}\right) \tag{10}$$

The average formulae for trapezoidal numbers can be derived similarly to Equations (9) and (10) and are presented as below.

7.4.2.3.3 Trapezoidal average formula

If $A_i = \left(a_1^{(i)}, b_1^{(i)}, b_2^{(i)}, a_2^{(i)}\right)$, $i = 1, \ldots, n$, are trapezoidal numbers, then

$$A_{ave} = \left(m_1, m_{M_1}, m_{M_2}, m_2\right)$$

$$= \frac{\left(a_1^{(1)}, b_1^{(1)}, b_2^{(1)}, a_2^{(1)}\right) + \ldots + \left(a_1^{(n)}, b_1^{(n)}, b_2^{(n)}, a_2^{(n)}\right)}{n}$$

$$= \frac{\left(\sum_{i=1}^{n} a_1^{(i)}, \sum_{i=1}^{n} b_1^{(i)}, \sum_{i=1}^{n} b_2^{(i)}, \sum_{i=1}^{n} a_2^{(i)}\right)}{n} \tag{11}$$

Weighted trapezoidal average formula is shown in Equation (12).

$$A_{ave}^{\omega} = \left(m_1^{\omega}, m_M^{\omega}, m_{M_2}^{\omega}, m_2^{\omega}\right)$$

$$= \omega_1 \left(a_1^{(1)}, b_1^{(1)}, b_2^{(1)}, a_2^{(1)}\right) + \ldots + \omega_n \left(a_1^{(n)}, b_1^{(n)}, b_2^{(n)}, a_2^{(n)}\right)$$

$$= \left(\sum_{i=1}^{n} \omega_i a_1^{(i)}, \sum_{i=1}^{n} \omega_i b_1^{(i)}, \sum_{i=1}^{n} \omega_i b_2^{(i)}, \sum_{i=1}^{n} \omega_i a_2^{(i)}\right) \tag{12}$$

The triangular and trapezoidal average and weighted average Equations (9) – (12) produce a result which can be interpreted as a conclusion or an aggregation of all meanings expressed by triangular or trapezoidal numbers $A_1,...A_n$ either of equal importance or of different importance expressed by weights ω_i.

The process of averaging involving fuzzy triangular and trapezoidal numbers presented here is a hybrid or cross section of classical statistics and fuzzy sets theory; it belongs to a new branch of science – fuzzy statistics.

7.4.2.3.4 Defuzzification of fuzzy average

The aggregation defined by a triangular or trapezoidal average number obtained using Equation (10) or (12) very often has to be expressed by a crisp value which best represents the corresponding average. This operation is called defuzzification and is demonstrated in Figure 7.3.

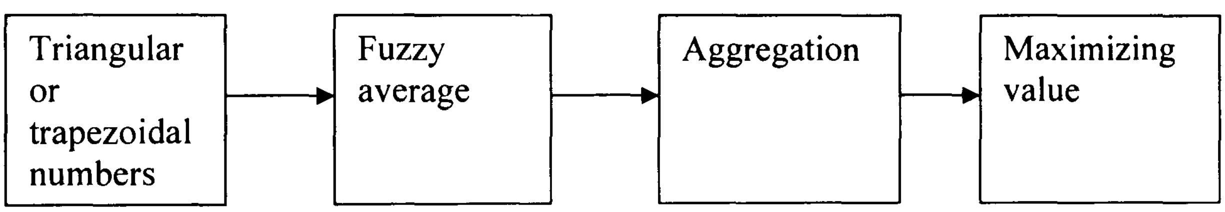


Figure 7.3. The process of defuzzification of fuzzy average.

First consider the defuzzification of $A_{ave} = (m_1, m_M, m_2)$ given in Equation (9). It looks plausible to select for that purpose the value m_M in the supporting interval $[m_1, m_2]$ of A_{ave}; m_M has the highest degree (one) of membership in A_{ave}. In other words, A_{ave} attains its maximum at m_M, which is called maximizing value.

$$x_{\max} = m_M \tag{13}$$

However, the operation defuzzification cannot be defined uniquely. In another word, there are various ways of defuzzification as proposed and adopted by different researchers. Three options are presented for defuzzifying $A_{ave} = (m_1, m_M, m_2)$, which are essentially statistical average formulas:

$$\begin{aligned}
&(1)\ x_{\max}^{(1)} = \frac{m_1 + m_M + m_2}{3} \\
&(2)\ x_{\max}^{(2)} = \frac{m_1 + 2m_M + m_2}{4} \qquad (14) \\
&(3)\ x_{\max}^{(3)} = \frac{m_1 + 4m_M + m_2}{6}
\end{aligned}$$

Equation (14) takes into consideration the contribution of m_1 and m_2 but gives different weight to m_M only.

If the triangular number A_{ave} is close to a central triangular number meaning that m_M is almost the middle of $[m_1, m_2]$, then Equation (13) gives a good crisp value $x_{\max} = m_M$. Then the three average formulas (1) to (3) in Equation (14) also produce numbers (maximizing values) close to m_M. Usually in applications the triangular average numbers appear to be in central form. However, the experts dealing with a given situation have to use their judgment when selecting a maximizing value.

The defuzzification procedure is presented as a block diagram shown in Figure 7.3. For the defuzzification of $A_{ave}^{\omega} = (m_1^{\omega}, m_M^{\omega}, m_2^{\omega})$, Equations (13) and (14) remain valid provided that $m_1^{\omega}, m_M^{\omega}$ and m_2^{ω} are substituted for m_1, m_M and m_2 correspondingly.

The defuzzification of the trapezoidal average $A_{ave} = (m_1, m_{M_1}, m_{M_2}, m_2)$ can be performed by an extension of Equations (13) and (14) using instead of m_M the midpoint of the flat segment m_{M_1} and m_{M_2}. The maximizing values are given as follows:

$$x_{\max} = \frac{m_{M_1} + m_{M_2}}{2} \qquad (15)$$

and

(1) $x_{\max}^{(1)} = \dfrac{m_1 + \dfrac{m_{M_1} + m_{M_2}}{2} + m_2}{3}$

(2) $x_{\max}^{(2)} = \dfrac{m_1 + m_{M_1} + m_{M_2} + m_2}{4}$ (16)

(3) $x_{\max}^{(3)} = \dfrac{m_1 + 2\left(m_{M_1} + m_{M_2}\right) + m_2}{6}$

For the defuzzification of $A_{ave}^{\omega} = \left(m_1^{\omega}, m_M^{\omega}, m_{M_2}^{\omega}, m_2^{\omega}\right)$, Equations (15) and (16) hold but $m_1^{\omega}, m_{M_1}^{\omega}, m_{M_2}^{\omega}$ and m_2^{ω} are substituted for m_1, m_{M1}, m_{M_2} and m_2 correspondingly.

7.5 A Safety Model - A Framework for Modelling Fire Safety using Approximate Reasoning and Fuzzy Averaging Method

A generic framework for modelling system safety using approximate reasoning and fuzzy averaging approaches is suggested and depicted in Figure 7.4. It is a convenient method for carrying out subjective assessment, therefore, it may provide a logical solution as it emulates the human reasoning process through synthesising human expert judgements within a specific domain of knowledge, codes and standards based on the guidelines and company policy using an approximate reasoning approach. In addition, a fuzzy averaging method is used in the later stage of the framework to deal with safety synthesis of the system (at system and sub-system levels) with complexity involving multi-experts, in a hierarchical structure. It provides a powerful and flexible platform for aggregation or amalgamation of experts' opinions or judgments.

The proposed framework for modelling system safety for risk analysis consists of five major steps. The first three outline all the necessary steps required for safety evaluation at the bottom level using an approximate reasoning approach. The fourth one describes the step involved in synthesising the estimates thus obtained in the first three steps, using a fuzzy averaging method to synthesise or amalgamate fire safety at higher levels of an engine room. A fuzzy averaging method is used to deal with hierarchical evaluation propagation issues without any loss of useful information. The final step describes the ranking and interpretation of the results.

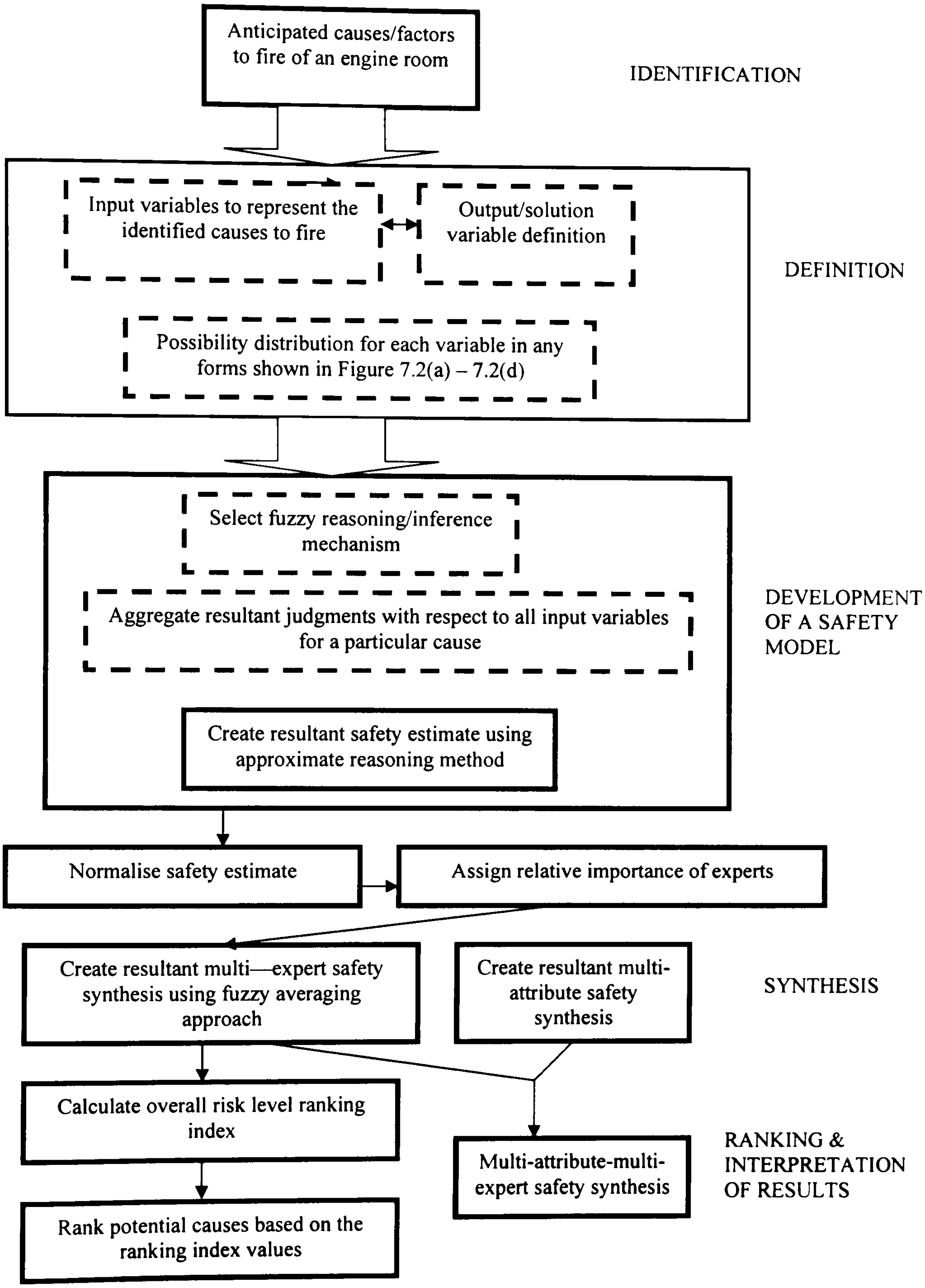


Figure 7.4. A framework for modelling system safety using approximate reasoning approach and fuzzy averaging method.

The five steps used in the framework are outlined as follows:

Step 1: Identification.

- Identify all the anticipated causes/factors to fire of an engine room in a hierarchical manner.

Step 2: Definition.

- Define fuzzy input variables (i.e., ***failure rate***, ***consequence severity***, ***failure consequence probability*** and ***control mechanism***) to describe the potential risk linguistically.
- Define fuzzy output/solution variables (i.e., ***safety estimates***).
- Select the type/types of fuzzy membership function used to delineate each input variable, and provide interpretation for each fuzzy set of each variable (in any forms shown in Figure 7.2(a) – (d)).

Step 3: Development of a safety model.

- Aggregate resultant judgments with respect to all input variables for a particular cause to technical failure.
- Create resultant safety estimate using fuzzy averaging method.
- Normalise safety estimates.
- Assign relative importance of each expert.

Step 4: Safety synthesis.

- Perform multi-expert safety synthesis in a hierarchy using fuzzy averaging method.
- Perform multi-attribute safety synthesis using fuzzy averaging method.

It is worth noting that in this step, in order to achieve a more effective and logical evaluation process, it is necessary to break down a complex system into simpler sub-systems and components in a hierarchical manner. The hierarchical framework of attributes or experts is used to guide the overall evaluation of multi-attributes or multi-experts or a combination of multi-attributes-multi-experts problems.

Step 5: Ranking and interpretation of results.

- Calculate overall risk level ranking index.
- Rank potential causes based on their ranking index values.
- Alternatively perform multi-attribute-multi-expert safety synthesis.

In fire risk study of a ship engine room, in many cases, subjective assessment (using linguistic variables instead of ultimate numbers in probabilistic terms) may be more appropriate to conduct analysis on the four parameters (*failure rate*, *consequence severity*, *failure consequence probability* and *control mechanism*) as they are always associated with great uncertainty, especially for an engine room with a high level of innovation.

Safety estimate is the only output fuzzy variable used in this study to produce safety evaluation for each cause to a technical failure at the bottom level of a hierarchical system. This variable is also described linguistically. In safety assessment, it is common to express a safety level by degrees to which it belongs to such linguistic variables as "*poor*", "*fair*", "*average*", and "*good*" that are referred to as safety expressions. The output set can be defined using fuzzy safety estimate sets in the same way as the fuzzy inputs.

Seven levels of linguistic variables may be used for ***failure rate***; five levels for ***consequence severity***, seven levels for ***failure consequence probability***, four levels for ***control mechanism*** and four levels for ***safety estimates***. The literature search indicates that four to seven levels of linguistic variables are commonly used to represents risk factors in risk analysis [Bell & Badiru, 1996] [Sii, et al., 2001c] [Wang, et al., 1995, 1996] [Wang, 1997].

It is possible to have some flexibility in the definition of membership functions to suit different situations. The application of categorical judgements has been quite positive in several practical situations [Schmucker, 1984]. It is also usually common and convenient for safety analysts to use categories to articulate safety information.

When describing ***failure rate***, ***consequence severity***, ***failure consequence probability***, ***control mechanism*** and ***safety estimate***, a linguistic variable may then be assigned with a membership function to a set of categories with regard to the particular condition. The typical linguistic variables for ***failure rate***, ***consequence severity***, ***failure consequence probability***, ***control mechanism*** and the ***safety estimate*** of a particular cause to a technical failure by an expert, or by a panel of experts may be defined and characterised as follows:

Failure rate describes the failure frequency in a certain time, which directly represents the number of failures anticipated during the design life span of a particular system or an item. Table 7.1 describes the range of the frequencies of the failure occurrence and defines the fuzzy set of ***failure rate***. To estimate the ***failure rate***, one may choose to use such linguistic variables as "*very low*", "*low*", "*reasonably low*", "*average*", "*reasonably frequent*", "*frequent*" and "*highly frequent*". The ***failure rate*** of this study is defined on the basis of the recorded fires from the NK investigation of accidents related to engine room fire. Figure 7.5 shows the fuzzy ***failure rate*** set definition.

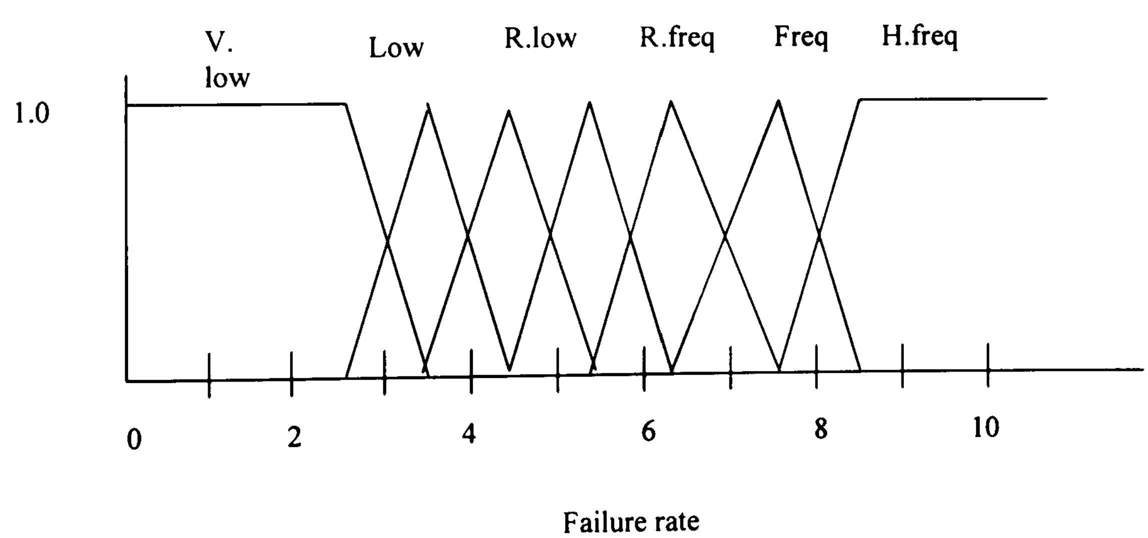


Figure 7.5. Fuzzy failure rate set definition.

Table 7.1. Failure rate.

Rank	***Failure rate***	Meaning (general interpretation)	Failure rate (1 / 25years) (interpretation in the context of engine room fire).
1,2,2.5	Very low	Failure is unlikely but possible during lifetime.	<1
3.5	Low	Likely to happen twice during lifetime.	2
4.5	Reasonably low	Between low and average.	5
5.5	Average	Occasional failure.	<10
6.5	Reasonably frequent	Likely to occur from time to time.	<20
7.5	Frequent	Repeated failure.	<29
8.5,9,10	Highly frequent	Failure is almost inevitable or likely to exist repeatedly.	>30

Consequence severity describes the magnitude of possible consequences, which is ranked according to the severity of the failure effects. One may choose to use such linguistic variables as "*negligible*", "*marginal*", "*moderate*", "*critical*" and "*catastrophic*". The fuzzy ***consequence severity*** set definition is shown in Figure 7.6.

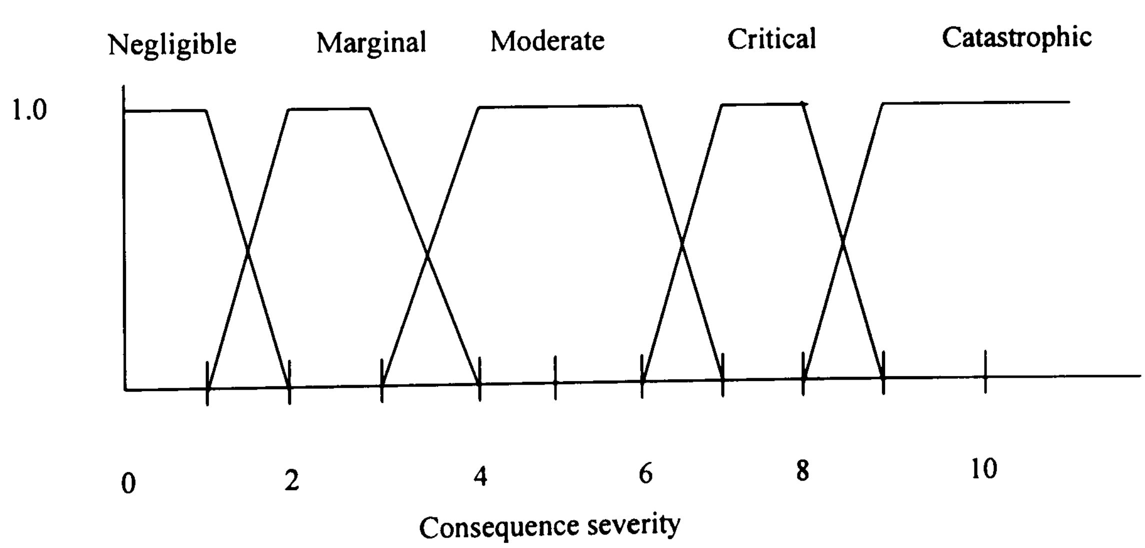


Figure 7.6. Fuzzy consequence severity set definition.

Table 7.2 shows the criteria used to rank the ***consequence severity*** of fire effects.

Table 7.2. Consequence severity.

Rank	*Consequence severity*	Meaning (generic interpretation in the context of engine room fire).
1	Negligible	At most an unscheduled maintenance required (service and operations can continue).
2, 3	Marginal	Possible single or multiple minor system damage. Operations interrupted slightly, and resumed to its normal operational mode within a short period of time (say less than 2 hours).
4, 5, 6	Moderate	Possible moderate system damage. Operations and production interrupted marginally, and resumed to its normal operational mode within a certain period of time (say no more than 4 hours).
7, 8	Critical	Possible major system damage.
9, 10	Catastrophic	Possible system loss.

The fuzzy ***failure consequence probability*** set definition is depicted in Figure 7.7 and the criteria used to describe the ***failure consequence probability*** are shown in Table 7.3.

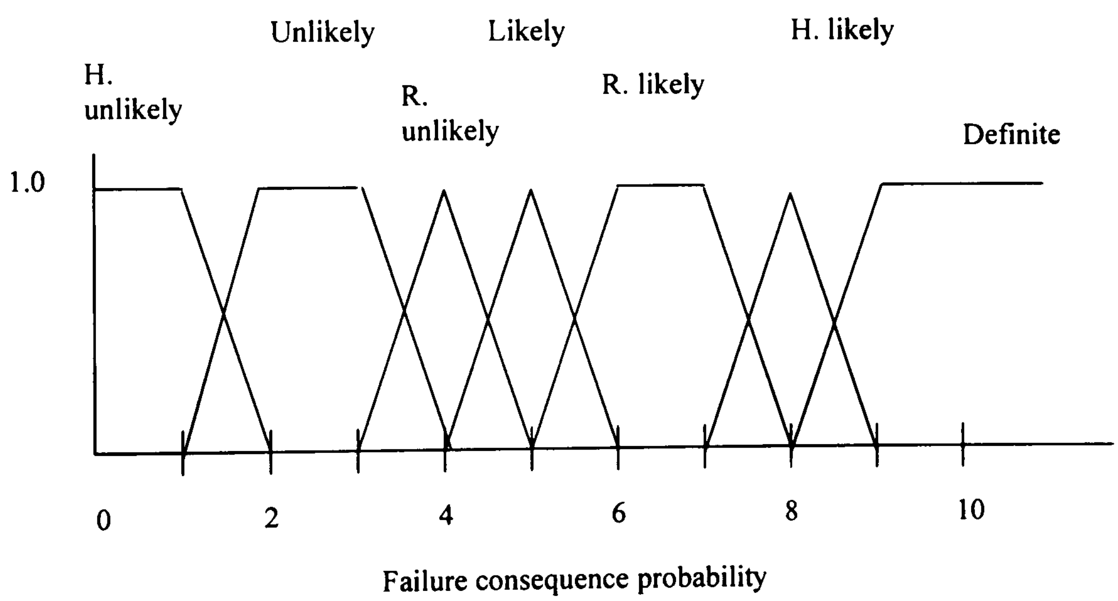


Figure 7.7. Fuzzy failure consequence probability set definition.

Table 7.3. Failure consequence probability.

Rank	***Failure consequence probability***	Meaning
1	Highly unlikely	The occurrence likelihood of possible consequences is highly unlikely given the occurrence of the failure event (extremely unlikely to exist on the system or during operations).
2,3	Unlikely	The occurrence likelihood of possible consequences is unlikely but possible given that the failure event happens (improbable to exist even on rare occasions on the system or during operations).
4	Reasonably unlikely	The occurrence likelihood of possible consequences is reasonably unlikely given the occurrence of the failure event (likely to exist on rare occasions on the system or during operations).
5	Likely	It is likely that consequences happen given that the failure event occurs (a programme is not likely to detect a potential design or an operational procedural weakness).
6,7	Reasonably likely	It is reasonably likely that possible consequences occur given the occurrence of the failure event (i.e. from time to time on the system or during operations, possibly caused by a potential design or operational procedural weakness).
8	Highly likely	It is highly likely that possible consequences occur given the occurrence of the failure event (i.e. often exist somewhere on the system or during operations due to a highly likely potential hazardous situation or a design and/or operational procedural drawback).
9,10	Definite	Possible consequences happen given the occurrence of a failure event.

Figure 7.8 and Table 7.4 illustrate the criteria used to describe the level of ***control mechanism*** (or availability of defence) in the design. The availability of ***control mechanism*** refers to Table 7.4, for the scale of its readiness with availability of mitigation measures. This is obviously an essential parameter to be considered in system safety assessment, especially at the early design stage. The level of control is described in linguistic terms such as ***"full control"***, ***"immediate control"***, ***"delayed control"*** and ***"no control"***. For example, ***"full control"*** provides a linguistic delineation that the failure or hazardous event can be detected at time of occurrence, both preventive and mitigation measures are available, or control measurement available and effective, or control not required as impact is very low. ***"Immediate control"*** on the other hand indicates that the system cannot detect the failure or

hazardous event at time of occurrence but preventive measure is available, or it can be detected at time of occurrence and mitigation measure is not available, or moderate control measure is available, however it is not an infallible system.

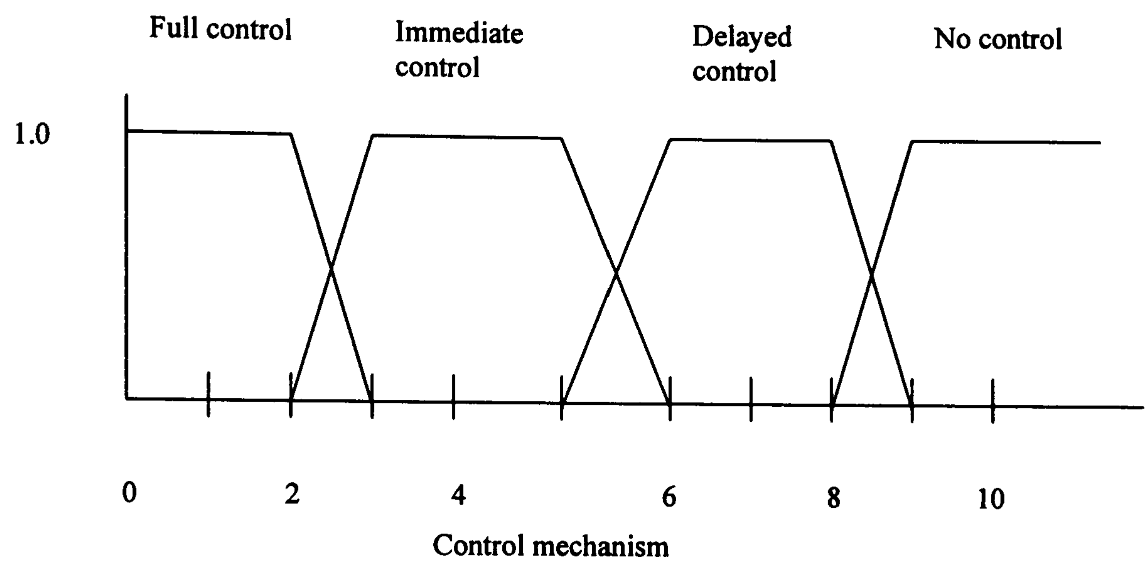


Figure 7.8. Fuzzy control mechanism set definition.

Table 7.4. Control mechanism.

Rank	*Control Mechanism*	Meaning
1, 2	Full control	Fire can be detected at time of its occurrence, both preventive and mitigation measures are available, or control measure is available and effective, or control is not required as impact is very low.
3, 4, 5	Immediate control	Fire cannot be detected at time of its occurrence but preventive measure is available, or fire can be detected at time of its occurrence and mitigation measure is available, or moderate control measure is available although not infallible.
6, 7, 8	Delayed control	Fire can be detected only after its occurrence and mitigation measure is available, or slight control measurement is available although not effective.
9, 10	No control	Fire cannot be detected and no mitigation measure is available, or control measure is not available even impact is not low.

With reference to the above fuzzy descriptions of ***failure rate, consequence severity, failure consequence probability*** and ***control measure***, it may be observed that the linguistic variables are not exclusive, as there are intersections among the defined linguistic variables. Inclusive expressions may make it more convenient for the safety analyst to judge a safety level. Overlapping functions are used to represent various linguistic variables because the experts and the literature concurred that in the analysis of the risks associated with a failure event/mode, the risk levels may have "gray" or ill-defined boundaries [Bell & Badiru, 1996].

Several sources such as historical records, operator's experience, statistical data, expert judgment, etc. can be used to carry out the judgment based on fuzzy descriptions. These approaches are mutually supporting each other and a combination of them is often the most effective way to determine the judgement. In the statistical data and information analysis the fuzzy descriptions may be derived based on statistical studies of the information in previous incident and accident reports or database systems. In-depth literature search may also be helpful. Skilled human analysts often have a good, intuitive knowledge of the behaviour of a system and the risks involved in various types of failures without having any quantitative model in mind. Fuzzy descriptions provide a natural platform for abstracting information based on expert judgements and engineering knowledge since they are expressed in a linguistic form rather than numerical variables. Therefore, experts often find fuzzy descriptions to be a convenient way to express their knowledge of a situation [Zimmermann, 1991].

The importance of approximate reasoning stems from the fact that human expert-judgements and engineering knowledge can often be represented in the form of fuzzy descriptions. Fuzzy descriptions based on these types of linguistic variables may be more natural and expressive than numerical numbers and criticality calculations. It is clear that such fuzzy descriptions can accommodate quantitative data such as ***failure rate, failure consequence probability*** and qualitative and judgmental data such as the ***consequence severity, control mechanism.*** The estimates can then be combined in safety evaluation.

The criteria of selecting fuzzy reasoning/inference mechanisms are always subjective issues and mainly based on user's preference. For the normal IF-THEN fuzzy rule inference, the general approach adopted is similar to that used in fuzzy expert and fuzzy control systems. However, in this chapter, a simplified fuzzy averaging method is introduced to perform approximate reasoning and synthesis.

The first module of fuzzy inference operation is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. Inputs can be represented by one of the following membership functions to suit the conditions under study:

- A single deterministic value.
- A closed interval defined.
- A triangular distribution.
- A trapezoidal distribution.

It is highly unlikely for selected experts to have the same importance, and weights of importance need to be utilised. The assessment of weight for each expert is an important decision for the analyst to make in view of the safety of the system under scrutiny. Each expert is assigned with a weight to indicate the relative importance of his or her judgment in contributing towards the overall safety evaluation process. The analyst must decide which experts are more authoritative. Weights are then assigned accordingly.

The fuzzy averaging method is used to perform safety synthesis at different levels (component, sub-system and system levels) of an engine room with a structure that is capable of being decomposed into hierarchy of levels. The number of levels required in safety synthesis is solely decided by the degree of complexity of a system under scrutiny.

The modelling framework of multi-attributes or multi-experts or a combination of both based on fuzzy averaging method has been developed to deal with such problems having a hierarchical structure of both qualitative and quantitative criteria with uncertainty. The fuzzy averaging method is different from most conventional Multiple Attribute Decision-Making (MADM) methods. Firstly, it employs a belief structure to represent an assessment as a distribution instead of a single numerical score. Secondly, it aggregates degrees of belief rather than scores. In this way, the fuzzy averaging approach can preserve the qualitative feature of subjective criteria in the process of criteria aggregation. The fuzzy averaging is a convenient method to aggregate or combine experts' opinions in producing a conclusion. It is a suitable tool for aggregation in qualitative safety or risk-based decision-support models.

The first three steps of the framework mainly focus on safety assessment of a single component of a particular sub-system. Step 4 is concerned with safety synthesis of a system at various levels such as:

- Multi-attribute safety synthesis of a sub-system due to a technical failure caused by various components done by an expert using an aggregation method - fuzzy averaging methods.
- Safety synthesis of a system due to a technical failure caused by various sub-systems done by an expert using any other aggregation methods.

The final step of the framework describes the calculation of overall risk level ranking index. Then the identified potential causes are ranked on the basis of their ranking index values.

To calculate risk ranking index values associated with various causes to technical failure, it is required to describe the four safety expressions, i.e., *{good, average, fair, poor}* using numerical values. The numerical values associated with the defined safety expressions can be designated by experts. Suppose K_1, K_2, K_3, K_4 represent the unscaled numerical values associated with '*good*', '*average*', '*fair*', '*poor*', respectively. Then K_1, K_2, K_3, K_4 can be represented as follows:

$$\{K_1, K_2, K_3, K_4\} = \{1, 0.8, 0.6, 0.2\} \qquad (17)$$

The safety estimate of cause *i* to technical failure can be obtained using the framework described in this subsection as follows:

$$\text{Safety Synthesis}_i = \{\mu_i^1 \text{ "}good\text{"}, \mu_i^2 \text{ "}average\text{"}, \mu_i^3 \text{ "}fair\text{"}, \mu_i^4 \text{ "}poor\text{"}\} \qquad (18)$$

The risk ranking index value R_i associated with cause i to technical failure can be defined as follows:

$$R_i = \sum_{j=1}^{4} \mu_i^j \times K_j, \quad i = 1,2,.....d, \text{ where } d \text{ is the number of causes to technical failure.} \tag{19}$$

Obviously, the R_i values obtained using the above formula can only show the relative risk level among all potential causes identified under study. The smallest R_i is ranked first as it deserves more attention to reduce its potential risk to As Low As Reasonably Practicable (ALARP). The largest R_i is ranked last to draw least attention and minimum effort for risk reduction measure consideration. A smaller R_i means that cause i of a sub-system is having relatively higher risk level and deserves more attention at the early design stages or the early stages of designing operational strategies. The ranking for each potential cause is then produced.

7.6 Case Study: Fire Risk Analysis of Ship Engine Room

In this section, a preliminary safety assessment is carried out on fire risk introduced by the malfunction of individual components associated with various sub-systems of a generic engine room. Only hardware failure caused risk is assessed here, though operational failure has been also recognised as one of the major causes of fire. In this case study, at the preliminary design stage there is only one expert taking part in the safety assessment. For the purpose of safety modelling, it is assumed that each input parameter (i.e., ***failure rate***, ***consequence severity***, ***failure consequence probability*** and ***control mechanism***) will be fed into the proposed safety model in terms of fuzzy membership functions in any one of the four forms as described in Figure 7.2 (a) – (d).

The selection of forms of membership function by an expert is dependent upon subjective judgment made pertaining to the level of ambiguity and uncertainty associated with the case as perceived by the expert, as well as his experience knowledge and understanding of the said system. The various forms of fuzzy membership function are capable of describing both "calculated risk" (i.e., those aspects with minimum uncertainty) and "uncertainty".

The safety critical elements were considered for an engine room. The generic engine room shown in Figure 7.1 is chosen as the system to be assessed by using the suggested framework. They consist of the following four main sub-systems:

1. Fuel Oil (FO).
2. Leakage Oil (LO).
3. Electrical Equipments (EE).
4. Turbo Charger (T/C) of Main Engine (M/E).

The expert judgment made on the four input parameters (i.e., ***failure rate***, ***consequence severity***, ***failure consequence probability*** and ***control mechanism***) using different forms of membership functions for representing technical failures associated with each sub-system is shown in Table 7.5 (a)–(d).

Table 7.5 (a) shows the assignment of membership functions and the result of risk analysis for components associated with sub-system #1 – FO and it is noted that only 7 major components are considered here. Table 7.5 (b) - (d) demonstrates the assignment of membership functions and the results for sub-systems #2, 3 and 4 (i.e, LO, Electrical Equipment and T/C of M/E). 6 components are considered for sub-system #2 – LO, 6 components assessed for sub-system #3 – Electrical Equipment, only 1 component for sub-system #4 – T/C of M/E.

The safety estimate for each component is computed by using fuzzy averaging method. Before the actual computation can be performed, each form of membership function has to be transformed into a trapezoidal membership function. For example, for component 1.1 of sub-system #1, the expert used the triangular membership function to describe the 4 input variables. The details are listed as follows:

Component 1.1 – M/E FO piping

4 input variables are originally described in the form of triangular membership function by the expert:

Failure rate = (6, 6.5, 7)
Consequence severity = (8, 9, 9.5)
Failure consequence probability = (7.5, 8, 8.25)
Control mechanism = (0.5, 2, 2.75)

After the transformation, the 4 input variables appear in the form of trapezoidal membership function:

Failure rate = (6, 6.5, 6.5, 7)
Consequence severity = (8, 9, 9, 9.5)
Failure consequence probability = (7.5, 8, 8, 8.25)
Control mechanism = (0.5, 2, 2, 2.75)

Applying the fuzzy averaging method, the *safety estimate* (Equation (11)) is obtained as:

Safety estimate $_{1.1}$ = {$\frac{6+8+7.5+0.5}{4}$=5.50 "Good";6.38 "Average";6.38 "Fair";6.81 "Poor"}

According to the framework found in Figure 7.4, the fuzzy averaging method is used to synthesise the information thus produced to assess the safety of the whole system. This step is concerned with safety synthesis of a system at various configurations such as:

- Multi-attribute safety synthesis at the component level – The synthesis of the four input variables to obtain the safety estimate of each component of each subsystem.

- Multi-attribute safety synthesis at the subsystem level - The synthesis of safety estimates of the components of the sub-systems of a generic engine room due to the fire failure estimated by an expert (Figures 7.4, 7.9 & 7.11).

- Multi-attribute safety synthesis at the system level - The synthesis of safety estimates of various subsystems of a generic engine room (Figures 7.4, 7.10 & 7.11).

Table 7.5 (a). Risk analysis for components associated with sub-system #1 – FO (raw data).

Component/ Activity	**Failure Rate**	**Consequence Severity**	**Failure Consequence Probability**	**Control Measure**	**Safety Estimate (Good,Average, Fair,Poor)**
1.1 M/E FO piping	(6, 6.5, 7)	(8, 9, 9.25)	(7.5, 8, 8.25)	(0.5, 2, 2.75)	5.50, 6.38, 6.38, 6.81
1.2 G/E FO piping	(5.25, 7.5, 9)	(6, 8.5, 10)	(7.5, 8, 8.5)	(0.25, 1, 1.5)	4.75, 6.25, 6.25, 7.25
1.3 Boiler FO piping	{5, 5.75, 6, 7.25}	{6, 6.5, 8, 8.25}	{7, 7.75, 8, 9}	{1.5, 1.8, 2.1, 3}	4.88, 5.45, 6.03, 6.88
1.4 FO tank	[2, 4]	[7.5, 8.5]	[7, 7.5]	[1, 1.7]	4.38, 4.38, 5.43, 5.43
1.5 FO tank sounding pipe	[1.5, 2.5]	[5, 7]	[6, 8]	[1.5, 1.8]	3.50, 3.50, 4.83, 4.83
1.6 G/E damage	(3, 3.5, 4)	(7, 8, 9)	(6, 7.5, 8)	(1.25 1.5, 1.75)	4.31, 5.13, 5.13, 5.69
1.7 Diesel oil purifier	{1, 1.5, 2, 2.5}	{5, 7, 8, 8.5}	{5.5, 6, 7, 7.5}	{0.25, 0.5, 0.75, 1}	2.94, 3.75, 4.38, 4.88

Table 7.5 (b). Risk analysis for components associated with sub-system #2 – LO (raw data).

Component/ Activity	**Failure Rate**	**Consequence Severity**	**Failure Consequence Probability**	**Control Measure**	**Safety Estimate (Good,Average, Fair,Poor)**
2.1 M/E LO piping	(4.5, 5, 7)	(6, 7, 8.5)	(7, 8.5, 9)	(1, 2.5, 3)	4.63, 5.75, 5.75, 6.88
2.2 M/E LO strainer	(0.75, 1.25, 2)	(5.05, 6, 7.75)	(6.25, 8, 8.5)	(3.05, 4, 4.5)	3.78, 4.81, 4.81, 5.69
2.3 G/E LO piping	[2, 3]	[6.5, 8.5]	[7, 7.5]	[1.25, 1.75]	4.19, 4.19, 5.19, 5.19
2.4 LO	{1, 1.5, 2, 2.5}	{6, 7, 8, 8.5}	{6, 6.5, 8, 8.5}	{0.5, 0.75, 1,	3.38, 3.94,

tanking For T//C of M/E				1.25}	4.75, 5.19
2.5 Strainer for T/C of M/E	(2.5, 3, 5)	(4.5, 5, 6)	(4.5, 5.5, 6)	(1, 1.5, 3)	3.13, 3.75, 3.75, 5.00
2.6 LO strainer For G/E	[1, 1.5]	[5, 7]	[6, 6.75]	[1.5, 1.75]	3.38, 3.38, 4.25, 4.25

Table 7.5 (c). Risk analysis for components associated with sub-system #3 – Electrical Equipment (raw data).

Component/ Activity	**Failure Rate**	**Consequence Severity**	**Failure Consequence Probability**	**Control Measure**	**Safety Estimate (Good,Average, Fair,Poor)**
3.1 Main switchboard	(4.5, 5, 9)	(6, 7, 7.25)	(7, 8, 9)	(1.25, 1.5, 1.8)	4.69, 5.38, 5.38, 6.76
3.2 Starter panels	(4, 5.5, 7)	(5.12, 6, 6.5)	(7.08, 7.5, 9)	(1.1, 2.75, 3.5)	4.33, 5.44, 5.44, 6.50
3.3 Generator	[4, 5]	[7.5, 8]	[2, 5]	[1, 1.5]	3.63, 3.63, 4.88, 4.88
3.4 Motor	{2, 3, 4, 4.25}	{5, 6, 6.5, 6.75}	{7.5, 7.75, 8.25, 9}	{4, 4.12, 5, 5.75}	4.63, 5.22, 5.94, 6.44
3.5 Transformer	(2, 2.5, 3)	(4, 6, 8)	(2, 4, 4.75)	(1, 2.5, 2.75)	2.25, 3.75, 3.75, 4.63
3.6 Electric heater	{0.1, 2, 3, 3.5}	{2, 2.5, 3, 6}	{5, 6.5, 7, 7.5}	{0.5, 0.75, 1, 2}	1.90, 2.94, 3.50, 4.75

Table 7.5 (d). Risk analysis for components associated with sub-system #4 – T/C of M/E (raw data).

Component/ Activity	**Failure Rate**	**Consequence Severity**	**Failure Consequence Probability**	**Control Measure**	**Safety Estimate (Good,Average, Fair,Poor)**
4.1 T/C of M/E	(6, 7, 8)	(7, 8.5, 9.5)	(6, 6.25, 6.75)	(2, 2.5, 3)	5.25, 6.06, 6.06, 6.81

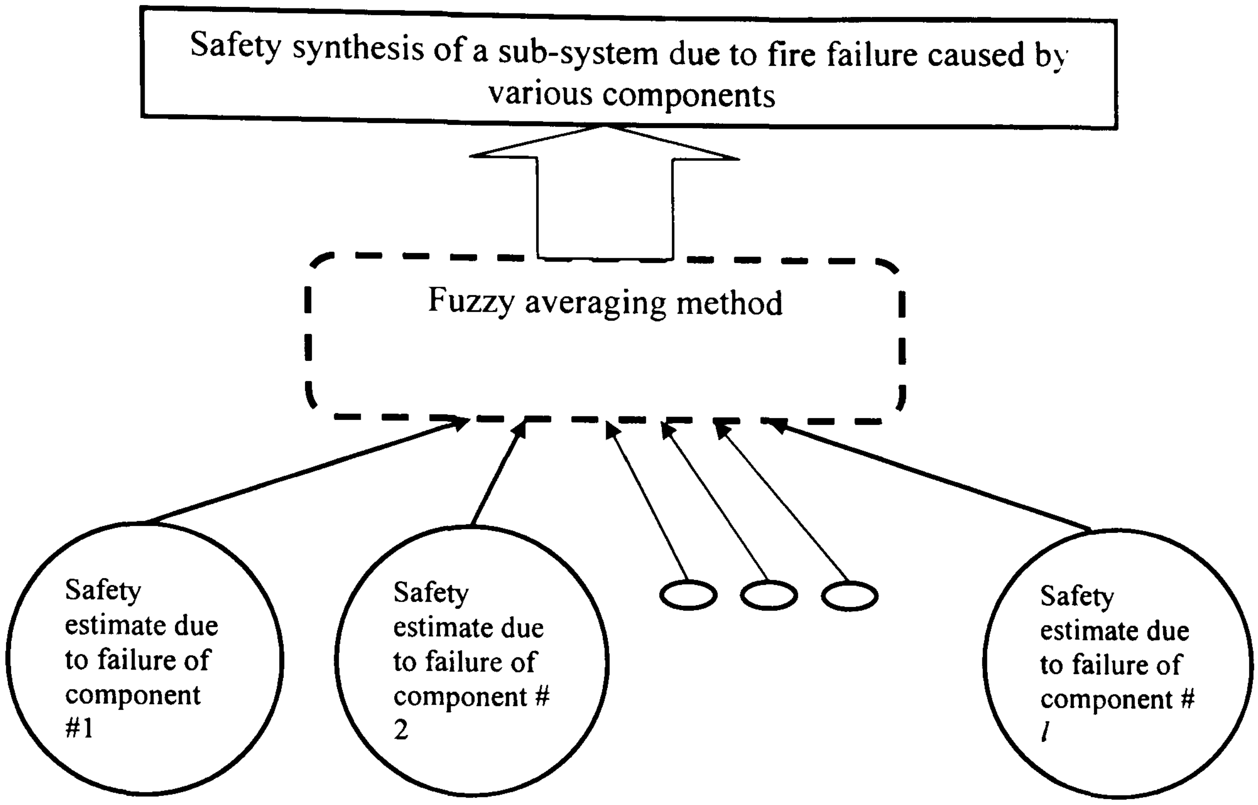


Figure 7.9. Multi-attribute safety synthesis of a sub-system due to a fire failure caused by various components estimated by an expert.

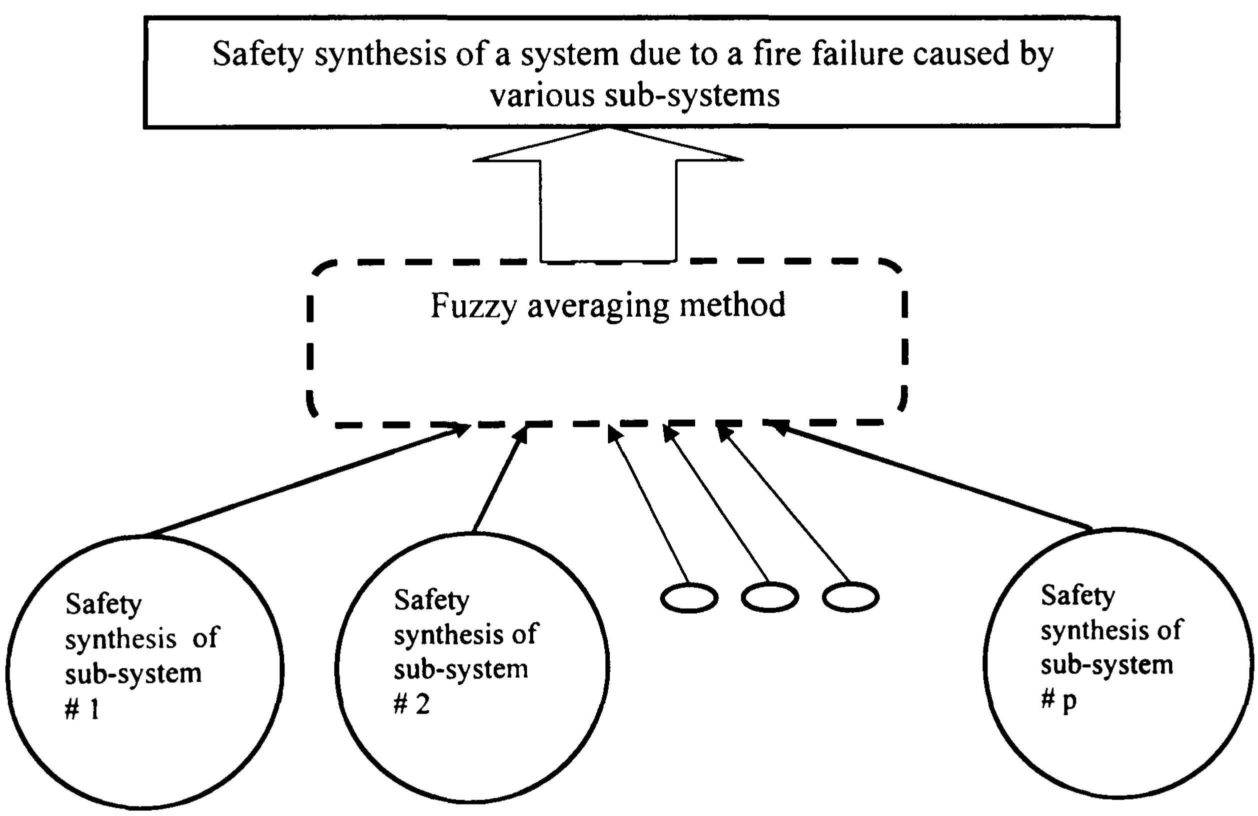


Figure 7.10. Safety synthesis of a system due to a fire failure caused by various sub-systems estimated by an expert.

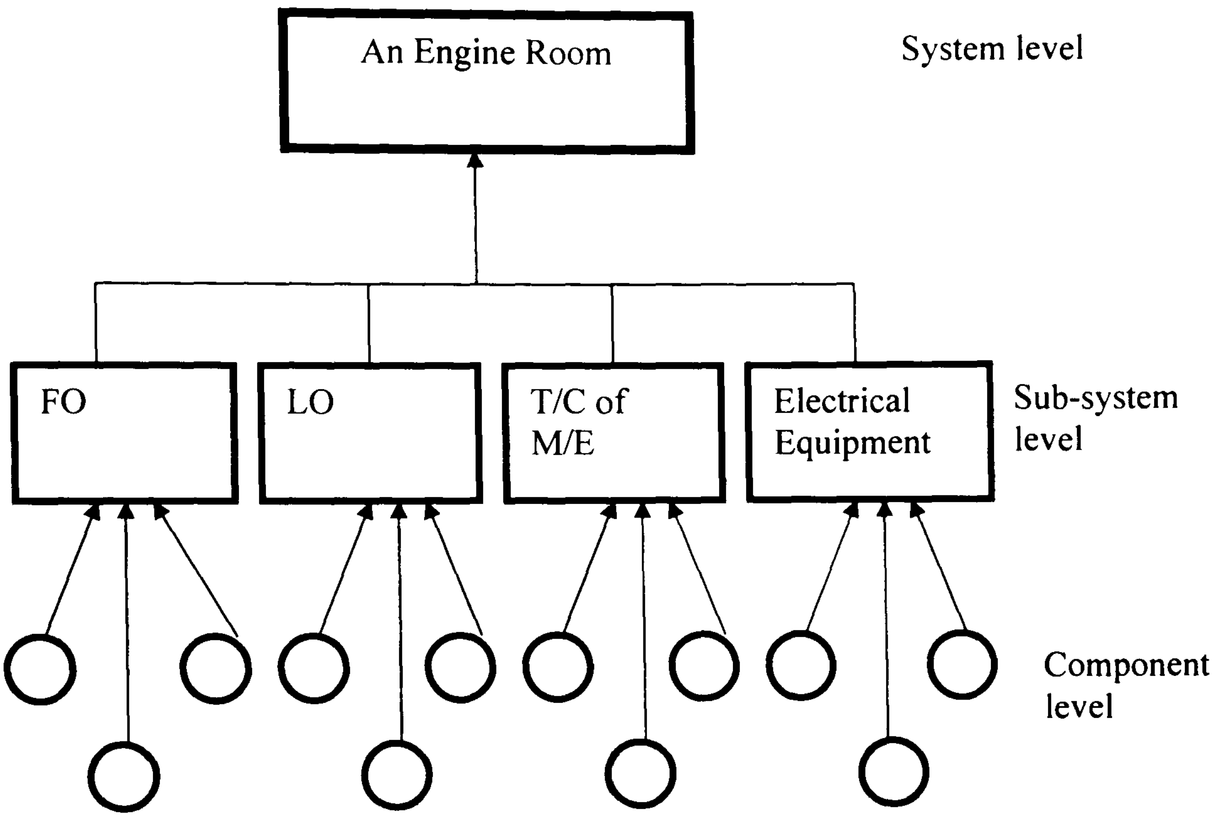


Figure 7.11. A generic hierarchical structure of an engine room.

7.6.1 Risk modelling at the component level

Upon normalization, the *safety estimate* for each component associated with each sub-system is shown in Table 7.6 (a) – (d). For example, the safety estimate for component 1.1 – M/E FO piping is:

Safety estimate $_{1.1}$ = $\{\frac{5.50}{5.50+6.38+6.38+6.81}$ =0.219 "Good";0.254 "Average";0.254 "Fair";0.273 "Poor"}

Table 7.6 (a). Risk analysis for components associated with sub-system #1 - FO [converted all membership functions into trapezoidal and normalised].

Component/ Activity	Failure Rate	Consequence Severity	Failure Consequence Probability	Control Measure	Safety Estimate (Good,Average, Fair,Poor)
1.1 M/E FO piping	{6, 6.5, 6.5, 7}	{8, 9, 9, 9.25}	{7.5, 8, 8, 8.25}	{0.5, 2, 2, 2.75}	0.219, 0.254, 0.254, 0.273
1.2 G/E FO piping	{5.25, 7.5, 7.5, 9}	{6, 8.5, 8.5, 10}	{7.5, 8, 8, 8.5}	{0.25, 1, 1, 1.5}	0.194, 0.255, 0.255. 0.296
1.3 Boiler FO piping	{5, 5.75, 6, 7.25}	{6, 6.5, 8, 8.25}	{7, 7.75, 8, 9}	{1.5, 1.8, 2.1, 3}	0.209, 0.235, 0.259, 0.296
1.4 FO tank	{2, 2, 4, 4}	{7.5, 7.5, 8.5, 8.5}	{7, 7, 7.5, 7.5}	{1, 1, 1.7, 1.7}	0.223, 0.223, 0.277, 0.277
1.5 FO tank sounding pipe	{1.5, 1.5, 2.5, 2.5}	{5, 5, 7, 7}	{6, 6, 8, 8}	{1.5, 1.5, 1.8, 1.8}	0.210, 0.210, 0.290, 0.290
1.6 G/E damage	{3, 3.5, 3.5, 4}	{7, 8, 8, 9}	{6, 7.5, 7.5, 8}	{1.25, 1.5, 1.5, 1.75}	0.213, 0.253, 0.253, 0.281
1.7 Diesel oil Purifier	{1, 1.5, 2, 2.5}	{5, 7, 8, 8.5}	{5.5, 6, 7, 7.5}	{0.25, 0.5, 0.75, 1}	0.184, 0.235, 0.275, 0.306

Table 7.6 (b). Risk analysis for components associated with sub-system #2 - LO [converted all membership functions into trapezoidal and normalised].

Component/ Activity	Failure Rate	Consequence Severity	Failure Consequence Probability	Control Measure	Safety Estimate (Good,Average, Fair,Poor)
2.1 M/E LO piping	{4.5, 5, 5, 7}	{6, 7, 7, 8.5}	{7, 8.5, 8.5, 9}	{1, 2.5, 2.5, 3}	0.201, 0.249, 0.249, 0.299
2.2 M/E LO strainer	{0.75, 1.25, 1.25, 2}	{5.05, 6, 6, 7.75}	{6.25, 8, 8, 8.5}	{3.05, 4, 4, 4.5}	0.198, 0.252, 0.252, 0.298
2.3 G/E LO piping	{2, 2, 3, 3}	{6.5, 6.5, 8.5, 8.5}	{7, 7, 7.5, 7.5}	{1.25, 1.25, 1.75, 1.75}	0.223, 0.223, 0.277, 0.277
2.4 LO tanking For T//C of M/E	{1, 1.5, 2, 2.5}	{6, 7, 8, 8.5}	{6, 6.5, 8, 8.5}	{0.5, 0.75, 1, 1.25}	0.196, 0.228, 0.275, 0.301
2.5 Strainer for T/C of M/E	{2.5, 3, 3, 5}	{4.5, 5, 5, 6}	{4.5, 5.5, 5.5, 6}	{1, 1.5, 1.5, 3}	0.200, 0.239, 0.239, 0.319
2.6 LO strainer For G/E	{1, 1, 1.5, 1.5}	{5, 5, 7, 7}	{6, 6, 6.75, 6.75}	{1.5, 1.5, 1.75, 1.75}	0.221, 0.221, 0.279, 0.279

Table 7.6 (c). Risk analysis for components associated with sub-system #3 – Electrical Equipment [converted all membership functions into trapezoidal and normalised].

Component/ Activity	Failure Rate	Consequence Severity	Failure Consequence Probability	Control Measure	Safety Estimate (Good,Average, Fair,Poor)
3.1 Main switchboard	{4.5, 5, 5, 9}	{6, 7, 7, 7.25}	{7, 8, 8, 9}	{1.25, 1.5, 1.5, 1.8}	0.211, 0.242, 0.242, 0.304
3.2 Starter panels	{4, 5.5, 5.5, 7}	{5.12, 6, 6, 6.5}	{7.08, 7.5, 7.5, 9}	{1.1, 2.75, 2.75, 3.5}	0.199, 0.251, 0.251, 0.299
3.3 Generator	{4, 4, 5, 5}	{7.5, 7.5, 8, 8}	{2, 2, 5, 5}	{1, 1, 1.5, 1.5}	0.213, 0.213, 0.287, 0.287
3.4 Motor	{2, 3, 4, 4.25}	{5, 6, 6.5, 6.75}	{7.5, 7.75, 8.25, 9}	{4, 4.12, 5, 5.75}	0.208, 0.235, 0.267, 0.289
3.5 Transformer	{2, 2.5, 2.5, 3}	{4, 6, 6, 8}	{2, 4, 4, 4.75}	{1, 2.5, 2.5, 2.75}	0.156, 0.261, 0.261, 0.322
3.6 Electric heater	{0.1, 2, 3, 3.5}	{2, 2.5, 3, 6}	{5, 6.5, 7, 7.5}	{0.5, 0.75, 1, 2}	0.145, 0.224, 0.267, 0.363

Table 7.6 (d). Risk analysis for components associated with sub-system #4 – T/C of M/E [converted all membership functions into trapezoidal and normalised].

Component/ Activity	Failure Rate	Consequence Severity	Failure Consequence Probability	Control Measure	Safety Estimate (Good,Average, Fair,Poor)
4.1 T/C of M/E	{6, 7, 7, 8}	{7, 8.5, 8.5, 9.5}	{6, 6.25, 6.25, 6.75}	{2, 2.5, 2.5, 3}	0.217, 0.251, 0.251, 0.281

7.6.2 Multi-attributes safety synthesis

Table 7.7 shows the results of multi-attributes safety synthesis (at the sub-system level) on technical fire risk of an engine room due to the FO, LO, Electrical

Equipment and T/C of M/E caused fire using the fuzzy averaging method. The synthesis is carried out without considering the relative weight of each sub-system/component, that is, using unity of weight.

Sub-system #1 – FO

Number of components = 7

Safety estimate $_{(FO)}$ = $\{\frac{0.219+0.194+0.209+0.223+0.210+0.213+0.184}{7} = 0.207$

"Good";0.238 "Average";0.266 "Fair";0.289 "Poor"}

Sub-system #2 – LO

Number of components = 6

Safety estimate $_{(LO)}$ = {0.207 "Good";0.235 "Average";0.262 "Fair";0.296 "Poor"}

Sub-system #3 – Electrical Equipment

Number of components = 6

Safety estimate $_{(EE)}$ = {0.189 "Good";0.238 "Average";0.263 "Fair";0.310 "Poor"}

Sub-system #4 – T/C of M/E

Number of components = 1

Safety estimate $_{(T/C\ of\ M/E)}$ = {0.217 "Good";0.251 "Average";0.251 "Fair";0.281 "Poor"}

The safety synthesis of the whole system is derived using the fuzzy averaging method as follows:

Safety synthesis of the whole system (i.e., the engine room) = $\{\frac{0.207+0.207+0.189+0.217}{4}$=0.205, "good"; 0.241, "average"; 0.261, "fair"; 0.293, "poor"}

Table 7.7. Multi-attribute safety synthesis on fire risk of FO, LO, Electrical Equipment and T/C of M/E.

Sub-system	Safety		Expressions	
	Good	Average	Fair	Poor
FO	0.207	0.238	0.266	0.289
LO	0.207	0.235	0.262	0.296
Electrical Equipment	0.189	0.238	0.263	0.310
T/C of M/E	0.217	0.251	0.251	0.281
Whole system	**0.205**	**0.241**	**0.261**	**0.293**

7.6.3 Safety synthesis of the system based on its sub-systems carrying different weights

The above evaluation is based on the assumption that each sub-system is of equal importance according to the opinions gathered from the expert. In practical applications, the subsystems may carry different weights in safety synthesis. The assignment of ranking scale in weight for each sub-system can be suggested by an expert based on his or her engineering judgment and past experience. This is to reflect his or her risk perception towards each sub-system. Suppose the four sub-systems are evaluated differently by their peers on a scale in weight from 0 to 10 as follows:

$r_1 = 10$ is given to $sub-system_1$ (sub-system #1, i.e., FO) in weight; $r_2 = 4$ to $sub-system_2$ (sub-system #2, i.e., LO); $r_3 = 3$ to $sub-system_3$ (sub-system #3, i.e., Electrical Equipment); r_4 = 3 to $sub-system_4$ (sub-system #4, i.e., T/C of M/E). The weights ω_i, $i = 1,2,3,4$, which express the relative importance of $sub-system_i$, $i = 1,2,3,4$ can be calculated using the following equation:

$$\omega_i = \frac{r_i}{r_1 + r_2 + r_3 + r_4} \tag{20}$$

$$\omega_1 = \frac{10}{10+4+3+3} = \frac{10}{20} = 0.5$$

$$\omega_2 = \frac{4}{10+4+3+3} = \frac{4}{20} = 0.2$$

$$\omega_3 = \frac{3}{10+4+3+3} = \frac{3}{20} = 0.15$$

$$\omega_4 = \frac{3}{10+4+3+3} = \frac{3}{20} = 0.15$$

Substituting these values into the weighted trapezoidal average Equation (12) gives:

$$Safety \quad synthesis(at \quad system \quad level)^{\omega}_{ave} = 0.5\left\{safety \quad estimate_{sub-system(1)}\right\} + 0.2\left\{safety \quad estimate_{sub-system(2)}\right\} + 0.15\left\{safety \quad estimate_{sub-system(3)}\right\} + 0.15\left\{safety \quad estimate_{sub-system(4)}\right\}$$

= {(0.5x0.207 + 0.2x0.207 + 0.15x0.189 + 0.15x0.217, "Good"); (0.5x0.238 + 0.2x0.235 + 0.15x0.238 + 0.15x0.251, "Average"); (0.5x0.266 + 0.2x0.262 + 0.15x0.263 + 0.15x0.251, "Fair"); (0.5x0.289 + 0.2x0.296 +0.15x0.310 +0.15x0.281, "Poor")}

= {0.206, "Good"; 0.239, "Average"; 0.263, "Fair"; 0.292, "Poor"}

The safety synthesis derived based on the weighted fuzzy averaging method as shown above has revealed that the safety estimate of the whole system can be interpreted as 20.6% "Good", 23.9% "Average", 26.3% "Fair" and 29.2% "Poor".

7.6.4 Ranking

The risk ranking for each sub-system based on the safety synthesis (Equation (17) (18)) obtained by using fuzzy averaging method is shown as follows:

$R_{sub\text{-}system(1)} = 1 \times 0.207 + 0.8 \times 0.238 + 0.6 \times 0.266 + 0.2 \times 0.289 = 0.615$

$R_{sub\text{-}system(2)} = 1 \times 0.207 + 0.8 \times 0.235 + 0.6 \times 0.262 + 0.2 \times 0.296 = 0.611$

$R_{sub\text{-}system(3)} = 1\times0.189+0.8\times0.238+0.6\times0.263+0.2\times0.310 = 0.599$

$R_{sub\text{-}system(4)} = 1\times0.217+0.8\times0.251+0.6\times0.251+0.2\times0.281 = 0.625$

Ranking = sub-system #4: sub-system #1: sub-system #2: sub-system #3.

or

Ranking = T/C of M/E: FO: LO: EE.

The smallest $R_{(3)}$ EE is ranked first as it deserves more attention to reduce its potential risk to As Low As Reasonably Practicable (ALARP). The largest $R_{(4)}$ T/C of M/E is ranked last to draw least attention and minimum effort for risk reduction measure consideration.

7.7 Conclusion

Performing the evaluation and fire risk assessment at this early stage will possibly provide further action learning opportunities which permit the design team to identify any fundamental deficiencies in the outline design of the selected concept. Moreover, this will enable the design team to explore and identify particular areas which have to be targeted during the various phases of design to prevent the occurrence of hazardous events such as fire or, if prevention is not possible, to detect events and control and mitigate their effects. Implementation of changes is always easier and economical before detailed design gets underway. The evaluation and assessment process can be repeated to study the effectiveness of any safety improvements which might be made subsequently.

The attempt in application of interval mathematics and possibility distribution such as approximate reasoning (based on fuzzy logic) method is different from conventional probability-based techniques which rely rather heavily on randomness and frequency on engineering systems. The safety modelling framework proposed in this chapter outlines and explains a philosophy for subjective safety modelling for fire risk analysis using approximate reasoning and fuzzy averaging methods. Various forms of membership functions that could be used effectively in representing fuzzy linguistic variables to qualify risk levels are discussed. The background of fuzzy averaging approach is also outlined.

The proposed framework offers a great potential in safety assessment and decision support of engineering systems, especially in the initial concept design stages of a relatively novel system where the related safety information is scanty or with great uncertainty involved or only linguistic-related information is available. Fire safety assessment using approximate reasoning approaches can integrate domain human experts' experience and safety engineering knowledge; at the same time information of difference properties from various sources can be transformed to become the knowledge base, used in the fuzzy logic inference process.

The modelling framework of multi-attributes or multi-experts or a combination of both based on fuzzy averaging method has been developed to deal with problems having a hierarchical structure of both qualitative and quantitative criteria with uncertainty. The fuzzy averaging method is different from most conventional Multiple Attribute Decision-Making methods and it is a convenient method to aggregate or combine experts' opinions in producing a conclusion.

The results obtained from a case study on an engine room have demonstrated that such a modelling framework provides fire safety analysts and designers with a convenient tool that can be used in a ship's engine room fire risk analysis.

References

Bell, P. M. & Badiru, A. B. (1996), "Fuzzy Modelling and Analytic Hierarchy Processing to Quantify Risk Levels Associated With Occupational Injuries – Part I: The Development of Fuzzy-Linguistic Risk Levels", IEEE Transactions on Fuzzy Systems, Vol 4, No 2, pp 124-131.

Foster, C. D. (1994), "Scientihic Investigation of Marine Shipping Fires and Explosions", Fire Safety on Ships: Developments into the 21st Century, Paper14, IMAS94, London, UK, 26-27 May.

Hakkinen, P. (1997), "Fire Resistant Engine Room", Fire at Sea International Conference, RINA, London, UK, November.

IMO (1997), "SOLAS-Consolidated Edition", London, UK.

Klir, J. G. & Yuan, B. (1995), "Fuzzy Sets and Fuzzy Logic, Theory and Applications", Prentice-Hall.

NKK (1994), "Engine Room Fire – Guidance for Prevention", Nippon Kaiji Kyokai, 161 pages, Japan.

Schmucker, K. J. (1984), "Fuzzy Sets, Natural Language Computations, and Risk Analysis", Computer Science Press.

Sii, H. S. (2000), "A Safety Model for Risk Analysis of Offshore Engineering Products Using Approximate reasoning and Evidential Reasoning Approaches", A Project Funded by EPSRC (GR/M24967) and HSE (D3727)", School of Engineering, Liverpool John Moores University, 81 pages, UK, December.

Sii, H. S. & Wang, J. (2000), "A Subjective Design for Safety Framework for Offshore Engineering Products", Workshops on Reliability and Risk Based Inspection Planning and ESRA Technical Committee on Offshore Safety, Zurich, Switzerland, 14-15 December.

Sii, H. S., Ruxton, T. & Wang, J. (2001a), "A Fuzzy-Logic-Based Approach to Qualitative Safety Modelling for Marine Systems", Reliability Engineering & System Safety, Vol 73, No 1, pp 19-34.

Sii, H. S., Ruxton, T. & Wang, J. (2001b), "Novel Risk Assessment Techniques for Maritime Safety Management System", International Journal of Quality & Reliability Management, Vol 7, No 2, pp 118-125.

Sii, H. S., Wang, J. & Ruxton, T. (2001c), "A Fuzzy-Logic-Based Approach to Subjective Safety Modelling for Maritime Products", Journal of the UK Safety & Reliability Society, Vol 21, No 2, pp 65-78.

Wang, J., Yang, J. B. & Sen, P. (1995), "Safety Analysis and Synthesis Using Fuzzy Sets and Evidential Reasoning", Reliability Engineering & System Safety, Vol 47, No 2, pp 103-118.

Wang, J., Yang, J. B. & Sen, P. (1996), "Multi-Person and Multi-Attribute Design Evaluations Using Evidential Reasoning Based on Subjective Cost Analysis", Reliability Engineering & System Safety, Vol 52, No 2, pp 113-129.

Wang, J. (1997), "A Subjective Methodology for Safety Analysis of Safety Requirements Specifications", IEEE Trans. Fuzzy Systems, Vol 5, No 3, pp 418-430.

Wang, J. & Ruxton, T. (1997), "Design for Safety", Journal of American Society of Safety Engineers, pp 23-29, January.

Wang, J. (Edited) (2001), "Marine and Offshore Safety Assessment", Journal of the UK Safety & Reliability Society, Vol 21, No 2.

Wang, L. X. (1997), "A Course in Fuzzy Systems and Control", Prentice-Hall, ISBN 0 13 540882 2.

Zimmermann, H. J. (1991), "Fuzzy Set Theory and Its Applications", Kluwer-Nijhoff Publishing, Hingham, Mass, USA.

CHAPTER 8 - A DESIGN-DECISION SUPPORT FRAMEWORK FOR EVALUATION OF DESIGN OPTIONS IN PASSENGER SHIP ENGINE ROOM

Summary

Most real world design evaluation and risk-based decision support combine quantitative and qualitative (linguistic) variables. Decision-making based on conventional mathematics that combines qualitative and quantitative concepts always exhibit difficulty in modelling actual problems. The successful selection process for choosing a design/procurement proposal is based on a high degree of technical integrity, safety levels and low costs in construction, corrective measures, maintenance, operation, inspection and preventive measures. However, the objectives of maximising the degree of technical performance, maximising the safety levels and minimising the costs incurred are usually in conflict, and the evaluation of the technical performance, safety and costs is always associated with uncertainties, especially for a novel system at the initial concept design stage. In this chapter, a design-decision support framework using a composite structure methodology grounded in approximate reasoning approach and evidential reasoning method is suggested for design evaluation of machinery space of a ship engine room at the initial stages. It is a Multiple Attribute Decision-Making (MADM) or Multiple Criteria Decision Making (MCDM) framework, which provides a juxtaposition of cost, safety and technical performance of a system during evaluation to assist decision makers in selecting the winning design/procurement proposal that best satisfies the requirement in hand. An illustrative example is used to demonstrate the application of the proposed framework.

8.1 Introduction

The purpose of safety based decision making is to take system safety as a design criterion to produce the best design with both technical and economical constraints being satisfied. MCDM techniques can then be employed to process the constructed model to produce efficient design solutions. In many cases, however, it may be difficult or even impossible to precisely determine the parameters of a probability distribution for a given event due to lack of evidence or due to the inability of the safety engineer to make firm assessments [Wang, et al., 1996].

The objective of risk-based design assessments during the preliminary design stage of a large engineering system such as a ship engine room is to provide safety-related input in the process of designing and developing a feasibly acceptable system. The concept design should comply with the mission requirements and commercial targets, as well as technical qualities together with the requirements given by the regulatory bodies. At the initial design stages, there is often inadequate data or imprecise information available when carrying out safety assessments for the system. Therefore, conventional approaches may not be capable of modelling safety, cost aspects and technical adequacy for design and operation decision support effectively and efficiently.

One of the main limitations associated with conventional Probabilistic Risk Assessment (PRA) methods is the utilisation of a probability measure to evaluate uncertainty. Much effort is required in defining and establishing the probability distribution for each contributing risk factor using historical data in estimating relative frequencies [Sii & Wang, 2003].

Uncertainty can be broadly classified into three categories, namely fuzziness, incompleteness and randomness [Blockley & Godfrey, 2001]. However, most analysts take it for granted that uncertainty is a model associated with randomness. In the appropriate circumstances, probability theory can be a powerful tool. However, many times the type of uncertainty encountered in marine projects does not fit the axiomatic basis of probability theory, simply because uncertainty in these projects is usually caused by the inherent fuzziness of the parameter estimate rather than randomness. Uncertainty involved in real world situations is often relating to the knowledge of systems rather than depending on chance.

One feasible way to deal with uncertainty in terms of fuzziness and incompleteness in design evaluation is to use fuzzy set theory. The use of fuzzy production rules in fuzzy inference system, where the conditional part and/or the conclusions contain linguistic variables, can handle these types of uncertainty well [Zimmerman, 1991]. This greatly reduces the need for an expert or a safety analyst, to know the precise point at which a risk factor exists. In this context, a safety model using approximate reasoning based on fuzzy logic approach may be more appropriate to model the risks of the system associated with incomplete safety information. Conventional approaches such as Fault Tree Analysis (FTA) and Failure Mode, Effects and Criticality Analysis (FMECA) have been widely used, but often fall short in their ability to permit the incorporation of subjective and/or vague terms as they rely heavily on supporting statistical information that may not be available.

The design process is one of choosing an overall design solution, deciding on the details of the solution and then checking that the undesirable occurrences do not occur. An assessment of the safety of systems may be carried out on the basis of different known safety concepts such as global safety factors, semi-probabilistic approach using partial safety factors, probabilistic approximation solution using first and second order reliability theory and probabilistic 'exact' solution [Moller, et al., 1999]. Inaccuracies and statistically non-describable uncertainties are either ignored in the application of these concepts or only accounted for approximately using crisp bounds.

In the evaluation of the safety and reliability of systems, how one quantitatively grasps the effects of uncertainty is important [Terano, et al., 1997]. The causes of uncertainty that one must consider, their origins, elements and other aspects are really diverse, and regardless of what approach is applied, it is always dependent on human judgements for their comprehensive evaluation. In another word, the lack of information and deficiencies of models must be made up by means of the general evaluation capacity of humans, who can grasp the essence of an object, even if it is vague and unclear. In order to make use of this kind of human ability and to handle a wide range of safety and reliability, a novel safety framework is required.

Often in marine engineering applications, engineers, safety analysts and managers are asked to make decisions on the basis of widely divergent objectives. For instance, contract proposals may be evaluated on the basis of technical merit, total cost incurred, ability to meet schedule requirements, and intangible attributes such as previous performance. In such situations experts are asked to evaluate the proposals based on their experiences and engineering judgements. Often, especially in early design stages for engineering systems with a high level of innovation, only qualitative or vague statements can be made, such as '*good performance*', or '*poor cost*', or '*quite safe*'. Experts then apply numerical ratings to these vague, or fuzzy terms to assist in the evaluation.

Fuzzy logic provides a means for evaluating alternatives where the objectives and criteria are vague and where the ranking criteria themselves vary in importance. Fuzzy logic is a subset of conventional logic that has been extended to allow for degrees of truth, i.e., truth-values between true and false [Sii & Wang, 2003].

Traditionally, in the marine industry, the primary objective in selecting a design/procurement option has been to select the one with the lowest cost estimate. However, in recent years, selection of the winning design/build proposal has been complicated by a trade-off among safety, cost and technical performance. Establishing criteria for the quantitative and qualitative selection of design/procurement proposals will enable designers to choose the proposal that best meets the needs described in the solicitation.

In the design/procurement proposal evaluation process, the assessment of technical performance, safety and costs is subject to uncertainty, especially with a project having a high level of innovation without much previous experience. In this chapter, the uncertainty in values of the input variables such as technical performance, safety and costs incurred and its impact on the aggregate evaluation results are characterised by the means of an approximate reasoning approach using fuzzy averaging method [Sii & Wang, 2003].

The proposed fuzzy-composite evaluation framework may be used as a useful tool to solve decision-making problems in situations where traditional methods cannot be applied satisfactorily. It is a multi-level, multi-objective programming method using fuzzy theory to represent the uncertainty in input variables in terms of membership functions or degrees of belief. The specific objectives of this chapter are twofold. The first objective is to develop a design-decision support framework based on a fuzzy-composite evaluation methodology and the second one is to apply the proposed framework to the technical performance-safety-costs trade-off analysis in a passenger ship engine room.

8.2 Concept of Fuzzy Logic & Delphi Method

8.2.1 Fuzzy logic

Fuzzy logic is not itself logic which is fuzzy, but rather it is a rigorous mathematical discipline for examining complex systems where the objectives and controlling parameters are vague or qualitative in nature. To understand fuzzy logic one must first examine classical mathematics. Classical set theory, the basis for most decision-making processes, allows for two options: either something is a member of a set or it is not a member.

In fuzzy set theory, developed by [Zadeh, 1965], everything is a matter of degree. On observing real world situations, the concepts of partial membership and gradual transition between membership and non-membership are intuitive. However, when analysis based on mathematical models is usually making use of assumptions, this inevitability forces a black or white view of the world due to limits of conventional logic. Fuzzy logic deals with shades of grey, allowing for partial truth, or grey areas. Since the transition from member to non-member appears gradually rather than abruptly, the fuzzy set introduces vagueness (with the aim of reducing complexity) by eliminating the sharp boundary dividing members of the set from non-members [Klir & Folger, 1988]. Thus, if an element is a member of a fuzzy set to some degree, the value of its membership function can be between *0* and *1*. When the membership function of an element can only have values *0* or *1*, the fuzzy set theory reduces to the classical set theory.

8.2.2 Application of the Delphi method in pooling expert judgement in design option assessment

Delphi is an iterative forecasting procedure characterised by three features: anonymity; iteration with controlled feedback; and statistical response [Dickey & Watt, 1978]. The Delphi method was first developed for market research and sales forecasting purposes [Goldstein, 1992] from the American defence industry. Project of Delphi was the name of a study undertaken by the Rand Corporation for the US Air Force in the early 1950s concerning the use of expert opinion [Robinson, 1991]. The objective of the study was to obtain the most reliable consensus of opinion of a group of experts by a series of intensive questionnaires interspersed with controlled opinion feedback [Linstone & Turoff, 1975].

The Delphi method can be characterised as an approach for structuring a group communication process so that the process is effective in allowing a group of individuals as a whole to deal with complex problems. Delphi is primarily a communication device, which is applied when the consensus of experts on an uncertain issue, often intangible, is desired [Linstone & Turoff, 1975]. It is conducted by rounds interspersed with group opinion and information feedback in the form of relevant statistical data.

It is vital that panel members remain unknown to one another and respond to a series of questionnaires. The iterative nature of the procedure generates new information for panellists in each round, enabling them to modify their assessments and project them beyond their own subjective opinions. It can represent the best forecast available from a consensus of experts.

The Delphi approach offers an additional advantage in situations where it is important to define areas of uncertainty or disagreement among experts. In these instances, Delphi can highlight topics of concern and evaluate uncertainty in a quantitative manner. Group evaluation of belief statements made by panel members is an explicit part of Delphi [Robinson, 1991]. Goldstein correctly pointed out that, although the group view has a higher probability of being correct than an individual, its success depends principally on the careful selection of the panel and the formulation of questions [Goldstein, 1975]. The major difficulties of Delphi, however, lie in maintaining the high level of response and in reaching and implementing a consensus [Robinson, 1991].

Prior to the design evaluation being performed by using the proposed composite structure, a panel of experts can be selected to carry out cost and technical performance assessments for each design option available subjectively using linguistic variables such as '*very low*' in capital cost and '*average*' in system integration. Then the panel is asked to assign degree of belief for each criterion based on the pre-defined expressions. For instant, the maintenance cost is described by the expressions such as {'*very low*', '*low*', '*average*', '*high*'}. The Delphi method is used to guide and extract the maximum amount of unbiased information from a panel of experts. Therefore, it is appropriate to adopt the Delphi method for obtaining assessments for each criterion for each alternative design option [Sii & Wang, 2003].

8.3 Development of Approximate Reasoning & MADM Model Based on Evidential Reasoning Method

8.3.1 Approximate reasoning (fuzzy logic: fuzzy averaging) model

Approximate reasoning and fuzzy logic are often used inter-changeably to indicate the process of expressing imprecise or approximate concepts and relationships. The main artificial intelligence mechanism behind a typical fuzzy safety model is its fuzzy inference engine. A fuzzy inference engine comprises the selection or development of the type/types of fuzzy membership function used to represent risk levels and fuzzy rule bases to generate fuzzy safety estimates. Linguistic variables are employed in the development of fuzzy membership function for each input parameter. The goal of fuzzy linguistic variables is to represent the condition of an attribute/ a parameter at a given interval. The attributes/parameters (input variables) considered in this study include ***failure rate, consequence severity*** and ***failure consequence probability*** of a cause to a technical failure. Another attribute considered is the associated ***control mechanism*** incorporated in the design or operation.

The four fundamental parameters ***failure rate, consequence severity, failure consequence probability*** and ***control mechanism*** are represented by natural languages, which can be further described by different types of membership function. A membership function is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between *0* and *1*. Four different types of membership function are used in this study. The simplest membership functions are formed using straight lines. These straight-line membership functions have the advantage of simplicity.

8.3.2 MADM model based on evidential reasoning method

MADM is defined as technical decision aids in evaluating and selecting alternative options, which are characterised by multiple attributes or criteria. MADM problems delineate a class of real world problems, which are having multiple attributes or objectives. Multiple attributes/objectives are often conflicting with each other and each attribute/objective is of different nature (based on different unit or scale of measurement). The key function of MADM is to obtain an optimal decision under certain constraints. This will help the decision-maker in evaluating alternative courses of action to achieve a certain goal or set of goals [Sii & Wang, 2003].

In order to achieve a more effective and logical evaluation process, it is necessary to break down the complex attributes into simpler sub-attributes in a hierarchical manner. The hierarchical framework of attributes is used to guide the overall evaluation of MADM problems.

Prior to the assessment undertaken by using an MADM model, a generalised set of evaluation grades is required. An attribute can be either assessed numerically or subjectively depending upon the nature and situation of the problem under study. The measurement of what is good or desirable about a design is based on its attributes.

In utility theory, the best judgement possible is related to the numerical value of one and the worst to zero. In this chapter, the general scale of evaluation grades, *H*, is defined as follows:

$H = \{H_1, H_2, H_3, H_4\}$ = {'*greatly preferred*', '*preferred*', '*moderately preferred*', '*slightly preferred*'}

The modelling framework for the MADM based on an evidential reasoning method has been developed to deal with MADM problems having a hierarchical structure of both qualitative and quantitative criteria with uncertainty [Yang, 2001]. The evidential reasoning framework is different from most conventional MADM methods. Firstly, it employs a belief structure to represent an assessment as a distribution instead of as a single numerical score. Secondly, it aggregates degrees of belief rather than scores. In this way, the evidential reasoning approach can preserve the qualitative feature of subjective criteria in the process of criteria aggregation. Using the four evaluation grades, the assessment of an attribute A_i, denoted by $S(A_i)$, can be represented using the belief structure as follows:

$$S(A_i) = \{(H_1, \beta_{i,1}), (H_2, \beta_{i,2}), (H_3, \beta_{i,3}), (H_4, \beta_{i,4})\} \tag{1}$$

where $1 \geq \beta_{i,n} \geq 0$ and $\beta_{i,n}$ is the degree of belief that the attribute A_i is assessed to the evaluation grade H_n. $S(A_i)$ reads that attribute A_i is assessed to the grade H_n to a degree of $\beta_{i,n} \times 100\%$ (n = 1, 2, 3 or 4).

There must not be $\sum_{n=1}^{4} \beta_{i,n} > 1$. $S(A_i)$ can be considered to be a complete distributed assessment if $\sum_{n=1}^{4} \beta_{i,n} = 1$ and an incomplete assessment if $\sum_{n=1}^{4} \beta_{i,n} < 1$. In the evidential reasoning framework, both complete and incomplete assessments can be accommodated [Yang, 2001]. In the case of an assessor, being unable to provide a precise judgement due to inadequacy of information available, the evidential reasoning approach allows a user to define a degree of belief of less than 1. No other MADM approaches can deal with this level of uncertainty and this helps reduce any inaccuracies introduced by further assumptions made. It is desirable that the assessment of all attributes should be complete. In design evaluation of an engineering artefact with a high level of innovation, at the initial concept stages, it is inevitable that the assessments of some criteria will be incomplete due to the highly subjective nature of the process and lack of available experience. The evidential reasoning model can handle both complete and incomplete assessments in a consistent manner. It has also been shown that numerical data can be modelled using belief structure through the equivalent transformation of information [Yang, 2001].

In the evidential reasoning framework, an MADM problem with M attributes A_i ($i = 1,...,M$), K options O_j ($j = 1,....,K$) and N evaluation grades H_n ($n = 1,...,N$) for each attribute is represented using an extended decision matrix with $S(A_i(O_j))$ as its element at the i^{th} row and j^{th} column where $S(A_i(O_j))$ is given as follows:

$$S\left(A_i\left(O_j\right)\right)=\left\{\left(H_n, \beta_{i,n}\left(O_j\right)\right), \quad n=1,.....,N\right\} \quad i=1,.....,M, \quad j=1,.....,K \quad (2)$$

It should be noted that an attribute is permitted to have its own set of evaluation grades that may be different from those of other attributes.

Based on the evidential reasoning framework the degrees to which a criterion is evaluated, with respect to one of the N evaluation grades, is directly dependent on the evidence that supports the evaluation. With the evidential reasoning approach, there is little compromise between the data collection process and effective evaluation, since the accuracy of the evaluation is directly proportional to the amount of accumulated evidence.

The major differences between the evidential reasoning approach and the conventional scoring methods come from the manner in which initial assessments are provided and aggregated. The evidential reasoning approach operates on distributed assessments (or evidence base mapping) instead of average scores and employs the evidence combination rule of the Dempster-Shafer theory to aggregate belief degrees [Yang, 2001]. This evidence based mapping process could be made less subjective by using guidelines and expert knowledge. The degree of objectivity in pooling evidence from various sources can be further improved by employing the Delphi method.

Suppose ω_i is the relative weight of the attribute A_i and is normalised so that $1 \geq \omega_i \geq 0$ and $\sum_{i=1}^{L} \omega_i = 1$, where L is the total number of attributes in the same group for aggregation. To simplify the description, only the combination of incomplete assessments is examined. The description of the recursive evidential reasoning algorithm capable of aggregating both complete and incomplete assessments can be found in literature [Yang & Xu, 2002]. Without loss of generality and for brevity of illustration, the evidential reasoning algorithm is presented below for combining two assessments only.

Suppose the two assessments $S(A_1)$ and $S(A_2)$ are given as follows:

$$S(A_1)=\{(H_1,\beta_{1,1}),(H_2,\beta_{1,2}),(H_3,\beta_{1,3}),(H_4,\beta_{1,4})\} \quad (3a)$$

$$S(A_2)=\{(H_1,\beta_{2,1}),(H_2,\beta_{2,2}),(H_3,\beta_{2,3}),(H_4,\beta_{2,4})\} \quad (3b)$$

The problem is to aggregate the two assessments $S(A_1)$ and $S(A_2)$ to generate a combined assessment $S(A_1)+S(A_2)$. Suppose $S(A_1)$ and $S(A_2)$ are both incomplete.

Let

$$m_{1,n}=\omega_1\beta_{1,n}\,(n=1,\ldots\ldots,4) \quad (4a)$$

$$m_{2,n}=\omega_2\beta_{2,n}\,(n=1,\ldots\ldots,4) \quad (4b)$$

$$\bar{m}_{1H}=1-\omega_1 \text{ and } \tilde{m}_{1H}=\omega_1\left(1-\sum_{n=1}^{4}\beta_{1,n}\right) \quad (4c)$$

$$\bar{m}_{2H}=1-\omega_2 \text{ and } \tilde{m}_{2H}=\omega_2\left(1-\sum_{n=1}^{4}\beta_{2,n}\right) \quad (4d)$$

$$m_{1H}=\bar{m}_{1H}+\tilde{m}_{1H} \text{ and } m_{2H}=\bar{m}_{2H}+\tilde{m}_{2H} \quad (4e)$$

In the evidential reasoning framework, $m_{1,n}$ and $m_{2,n}$ are referred to as basic probability masses. While m_{1H} and m_{2H} are masses of the remaining belief unassigned after commitment of belief to all $H_n\,(n=1,....,4)$, $\bar{m}_{1H}$ is the first part of the remaining probability mass that is not yet assigned to individual grades due to the fact that attribute A_1 only plays one part in the assessment relative to its weight and $\tilde{m}_{1H}$ is the second part of the remaining probability mass unassigned to individual grades, which is caused due to the incompleteness in the assessment $S(A_1)$. The evidential reasoning algorithm is used to aggregate the basic probability masses to generate combined probability masses, denoted by $m_n\,(n=1,.....,4), \bar{m}_H$ and $\tilde{m}_H$ using the following equations [Yang & Xu, 2002]:

$$m_n = k\left(m_{1,n}m_{2,n} + m_{1H}m_{2,n} + m_{1,n}m_{2H}\right), \quad n = 1,.....,4 \tag{5}$$

$$\bar{m}_H = k(\bar{m}_{1H}\ \bar{m}_{2H}) \text{ and } \tilde{m}_H = k(\tilde{m}_{1H}\ \tilde{m}_{2H} + \tilde{m}_{1H}\ m_{2H} + m_{1H}\ \tilde{m}_{2H}) \tag{6}$$

where $$k = \left(1 - \sum_{t=1}^{4}\sum_{\substack{n=1\\ n\neq t}}^{4} m_{t,1}m_{2,n}\right)^{-1} \tag{7}$$

The combined probability masses can then be aggregated with the additional assessments in the same fashion. The process is repeated until all assessments in the group are aggregated. The final combined probability masses are independent of the order in which individual assessments are aggregated.

If there are only two assessments, the combined degrees of belief $\beta_n\,(n=1,.....,4)$ and β_H , the later being the unassigned degree of belief representing the extent of incompleteness in the overall assessment are generated by the following expression:

$$\beta_n = \frac{m_n}{1-\bar{m}_H}, \quad n = 1,......,4 \text{ and } \beta_H = \frac{\tilde{m}_H}{1-\bar{m}_H} \tag{8}$$

8.4 A Design-Decision Support Framework Using a Composite Structure Methodology for Design Options Evaluation

8.4.1 A design-decision support framework

This section proposes a design-decision support framework using a composite structure methodology based on approximate reasoning approach and evidential reasoning method for design options evaluation for marine engineering systems. The framework is a multi-criteria decision-making methodology to assist decision makers in solving the design options selection problems where there are conflicting objectives, the objectives have different preferences (weights), and the value of each input variable is having certain level of uncertainty. This is certainly the case that occurs in the process for selecting the best design option, that is, the one that best satisfies the requirements of design/procurement projects. The framework consists of the following steps:

Step 1: Identify and define the hierarchical structure consisting of criteria, sub-criteria and sub-sub-criteria.

Step 2: Group basic or first-level criteria (sub-sub-criteria) into progressively fewer, more general groups (second-level criteria or sub-criteria).

Step 3: Use approximate reasoning approach, Delphi method and fuzzy averaging to represent the uncertainty in the basic criteria.

Step 4: Determine the relative weights of the criteria in the hierarchical structure and use Intelligent Decision System (IDS) via Evidential Reasoning [Yang & Xu, 2004]to synthesise all the related basic criteria into second level criteria.

Step 5: Define a utility space to evaluate the different second level criteria on the same scale.

Step 6: Perform system synthesis for each design option using IDS.

Step 7: Compare the options by computing the preference estimate for each design option using IDS.

Step 8: Rank the alternative options in order of preference.

Figure 8.1 depicts the generic framework.

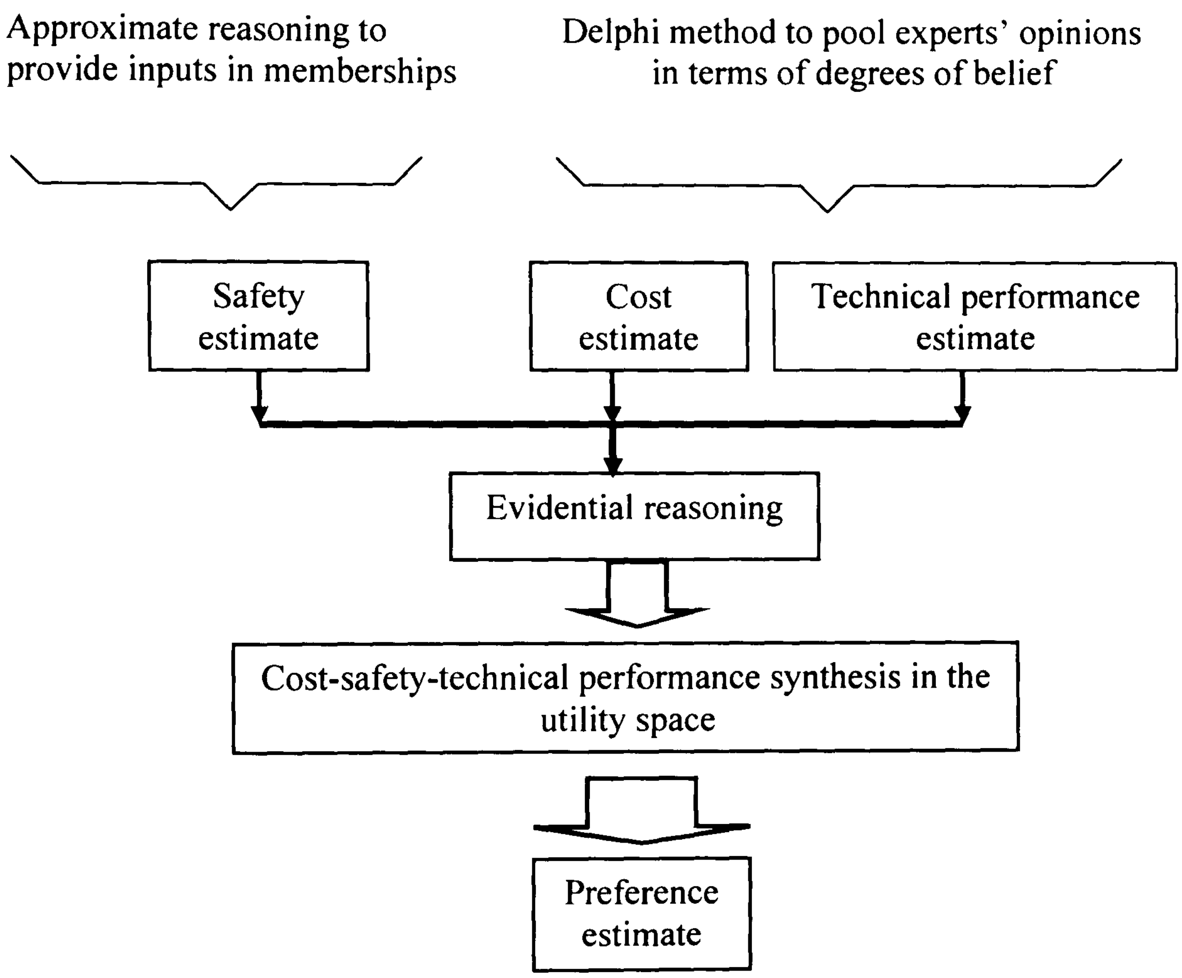


Figure 8.1. Subjective evaluation framework for various design options.

The following will delineate each step in detail:

Step 1: Identify and define the hierarchical structure consisting of criteria, sub-criteria and sub-sub-criteria.

The first step is to define all the basic criteria (first level) (sub-sub-criteria), second level criteria (sub-criteria) and the system (criterion) that are used in the design-decision support evaluation process. It is essential to list all the basic criteria and the salient characteristics of the system.

Step 2: Group basic criteria (first level)(sub-sub-criteria) into progressively fewer, more general groups (second-level)(sub-criteria).

Basic criteria are grouped into appropriate sub-criteria. The sub-criteria are then further grouped in the system-criteria. For example, the eight basic criteria for evaluation of a passenger ship engine room are shown in Figure 8.2. The set of basic (first-level) criteria is grouped into a smaller subset of second-level criteria. For example, the basic criteria such as capital cost, maintenance cost, operational cost and inspection cost can be grouped into cost in general, which is an element of the subset of the second level criteria. The other two second-level criteria are safety and technical performance. The third-level is considered as the final-level or system-level. The system criterion can be formed by combining the three second-level criteria (i.e., safety, costs and technical performance).

Step 3: Use approximate reasoning approach and Delphi method to evaluate the basic criteria and use fuzzy averaging to represent the uncertainty in the basic criteria.

Safety Modelling

The four fundamental parameters used to assess the safety level of a maritime system on a subjective basis are the ***failure rate, consequence severity, failure consequence probability*** and ***control mechanism***. ***Safety estimate*** is the only output fuzzy variable used in this study to produce the safety evaluation for each element at the bottom level of a hierarchical system. In safety assessment, it is common to express a safety level by degrees to which it belongs to such linguistic variables as "*poor*", "*fair*", "*average*", and "*good*" that are referred to as safety expressions.

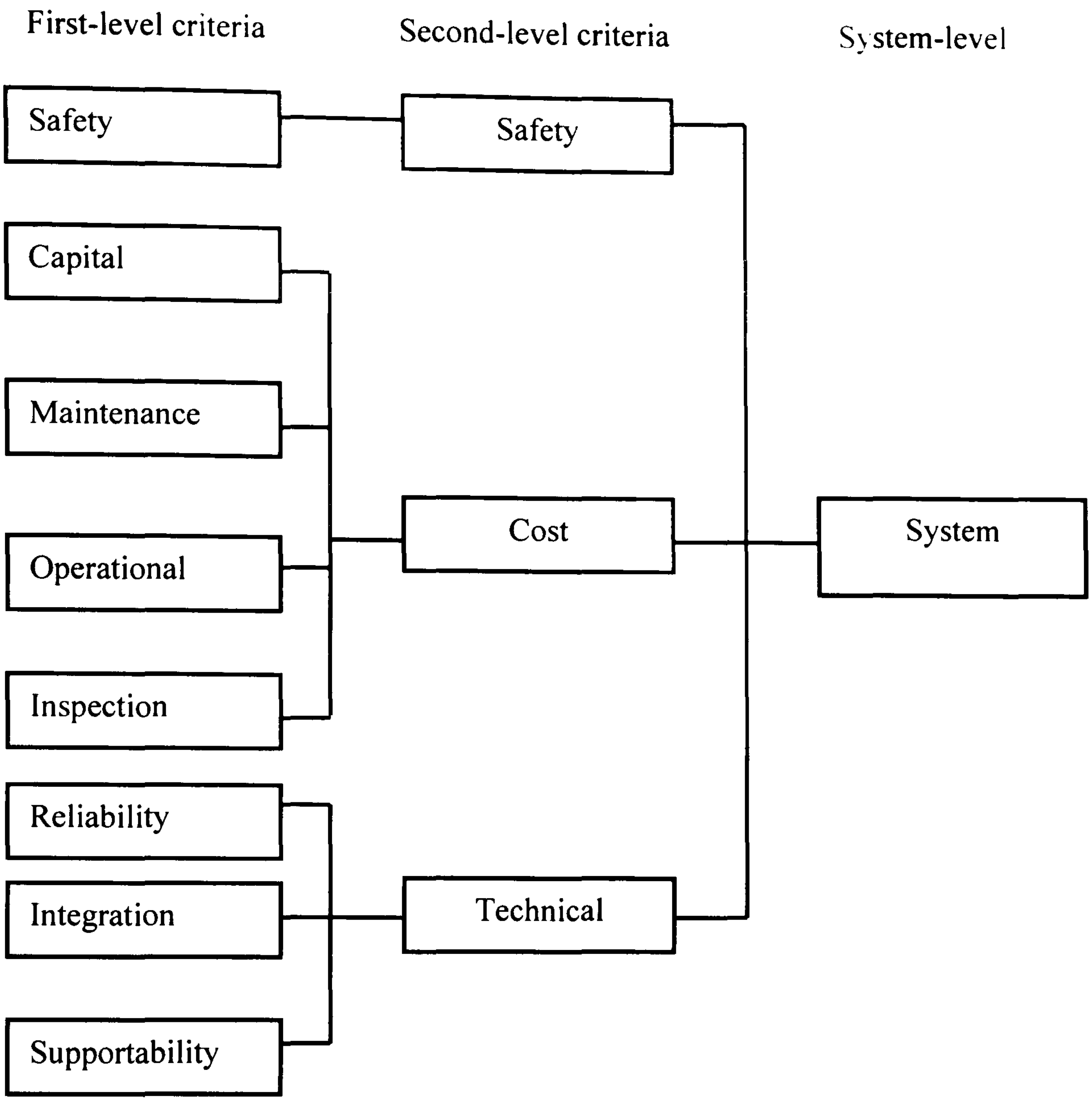


Figure 8.2. The composite procedure for evaluation of the passenger ship engine room.

Cost Modelling

The cost incurred for the safety and technical performance improvement associated with a design option is usually affected by many factors. The capital cost, maintenance cost, operational cost or inspection cost incurred for a design option can be described using linguistic variable such as {'*very low*', '*low*', '*average*', '*high*'}, which are referred to as cost expressions. The assignment of the four membership degrees to the four cost expressions is based on the engineering judgement and experience of the engineering team in terms of degrees of belief.

Technical Performance Modelling

The basic criteria related to technical performance such as reliability, system integration and supportability are used to describe the technical strength of each design option. These basic criteria are assessed in a similar way based on engineering judgement and experiences of a team of personnel with strong technical background. The reliability, system integration or supportability for a design option can be described using linguistic terms such as those used for cost modelling, i.e., {'*very low*', '*low*', '*average*', '*high*'}, which are referred to as technical performance expressions.

The values of the basic criteria for each design option are described in degrees of belief in accordance with the pre-defined fuzzy expressions. The Delphi method is applied to improve the objectivity of degrees of belief assessment made by a panel of experts.

<u>Step 4: Determine the relative weights of the criteria in the hierarchical structure and use IDS to synthesise all the related basic criteria into second level criteria.</u>

Relative weights of the criteria at both the first level and second level of the hierarchical structure are determined. Many methods including the Delphi technique can be used to obtain such weights. The evidential reasoning method is then used to synthesise all the basic criteria. This is to create second-level criteria for further analysis.

<u>Step 5: Define a utility space to evaluate the different second level criteria on the same scale.</u>

The selection of a design proposal relies on cost, safety and technical performance implications in a particular situation. This requires the synthesis of cost, safety and technical performance estimates for each design option in a rational manner. The cost, safety and technical performance are described in such a way that the evidential reasoning approach can be used to carry out such a synthesis in order to avoid loss of useful information. However, the safety and technical performance associated with and cost incurred for each design option are described in terms of safety, technical performance and cost expressions, respectively. It is therefore necessary to define a utility space to evaluate cost, safety and technical performance on the same scale to expedite the synthesis process using evidential reasoning. Four utility expressions are defined as {'*greatly preferred*'; '*preferred*'; '*moderately preferred*'; '*slightly preferred*'}. The safety and technical performance expressions associated with and cost incurred for each design option are then mapped onto the generalised utility space and expressed in terms of utility expressions. For example, '*greatly preferred*' corresponds to '*good*' in safety expressions, '*very low*' in cost expressions and '*high*' in technical performance expressions.

This step defines a common utility space in order to convert all the second-level criteria of different nature on the same scale. The second-level criteria are then mapped onto the utility space and expressed in terms of the utility expressions.

Step 6: Perform system synthesis for each design option using IDS.

The IDS is applied to carry out the synthesis of various second-level criteria, i.e., cost, safety, and technical performance. This is to achieve the final evaluation at the system level.

Step 7: Compare the options by computing the preference estimate for each design option using IDS.

The preference degrees associated with the available design options can be obtained by synthesising the safety and technical performance associated with and cost incurred for each design options using the evidential reasoning approach. The numerical values are assigned here to describe the four utility expressions (i.e. "*greatly preferred*"; "*preferred*"; "*moderately preferred*"; "*slightly preferred*") in normalised form as follows: $K = [K_1; K_2; K_3; K_4] = [1; 0.8; 0.6; 0.2]$. The attributes of cost, safety and technical performance can be considered to carry different weights (i.e. having different degrees of importance) for different situations while conducting the design selection.

Step 8: Rank the alternative options in order of preference.

Design selection can be carried out on the basis of the preference degrees associated with the available design options with regard to the particular considerations of cost, safety and technical performance using IDS.

8.5 Case Study

Under most circumstances, assessments of options/alternatives are usually performed on the basis of evaluation inputs that are crisp (single values are used) but subjective. In this case the criteria may be presented as a range of possible values instead of crisp values. The following example is used to illustrate the applicability of the proposed framework in design option evaluation.

The machinery space of a passenger ship must be evaluated on the basis of a number of factors, such as safety, cost and technical performance. Assume that four options are being considered for an engine room. **Option # 1** is a conventional ship engine room design without much innovation involvement. **Option # 2** is a new design with a high safety and reliability level as well as novel fire alarms. Its capital and maintenance costs are comparatively more expensive than the conventional design (option # 1) as the design is capable of reducing the effect from fire accidental impact. **Option # 3** is another design associated with some novel design features such as high technology fire extinguisher (i.e., CO_2, foam, chemical), which provides improved system safety and supportability. However, these novel design features inevitably increased the maintenance as well as capital costs. **Option # 4** provides a generally good safety and reliability margins with novel fire control systems. Its design also provides improved system integration and supportability, but it requires higher costs in both maintenance and inspection throughout its operational life.

All the four options are hypothetically prepared for illustration purposes. The engineering design team will perform a technical review for acceptability in meeting the mandatory requirements in terms of safety, cost and technical aspects of the request for the four options. The engineering design team may be composed of personnel with various professional expertise in the fields ranging from engineering design, safety analysis, cost estimation, utility engineering, etc.

The design evaluation is performed using the proposed framework as follows:

Step 1: Identify and define the hierarchical structure consisting of criteria, sub-criteria and sub-sub-criteria.

The hierarchical structure of the design evaluation is depicted in Figure 8.2.

Step 2: Group basic criteria into progressively fewer, more general groups.

The second step in the evaluation is to group appropriate basic criteria (first-level) such that they reduce to a single composite criterion (second-level). This grouping is shown in Figure 8.2. The basic criteria are known as the first-level criteria, and include safety, capital cost, maintenance cost, operational cost, inspection cost, reliability, easy system integration and supportability. The second-level criteria are safety, cost and technical performance. The final composite criterion is the system.

Step 3: Use approximate reasoning approach, Delphi method and fuzzy averaging to represent the uncertainty in the basic criteria.

The experts are requested to assess degrees of belief for each criterion in each design option according to the pre-defined fuzzy expressions. The Delphi method is then used to extract the maximum amount of unbiased assessment from a panel of experts. For example, the assessments made for capital cost for design option #1 by five experts is shown in Tables 8.1. The deviations of each expert's judgement from the average are given in Table 8.2.

Table 8.1. Assessment presented by experts for capital cost in design option #1 (Delphi method round 1).

Expert, Ei	Fuzzy	Expressions		
	'very low'	*'low'*	*'average'*	*'high'*
E_1	0.10	0.45	0.30	0.15
E_2	0.05	0.60	0.25	0.10
E_3	0.15	0.55	0.10	0.20
E_4	0.00	0.70	0.25	0.05
E_5	0.25	0.50	0.20	0.05
Average	0.11	0.56	0.22	0.11

Table 8.2. Deviation from average.

Expert, E_i	Fuzzy	Expressions		
	'very low'	*'low'*	*'average'*	*'high'*
E_1	-0.01	-0.11	0.08	0.04
E_2	-0.06	0.04	0.03	-0.01
E_3	0.04	-0.01	-0.12	0.09
E_4	-0.11	0.14	0.03	-0.06
E_5	0.14	-0.06	-0.02	-0.06

Suppose the first round assessment is not satisfied with the level of deviations presented. Then the results on deviation and average for each fuzzy expression are given to each expert for reconsideration.

Table 8.3. Assessment presented by experts for capital cost in design option #1 (Delphi method round 2).

Expert, E_i	Fuzzy	Expressions		
	'very low'	*'low'*	*'average'*	*'high'*
E_1	0.16	0.57	0.19	0.08
E_2	0.14	0.53	0.22	0.11
E_3	0.15	0.54	0.20	0.11
E_4	0.13	0.56	0.21	0.10
E_5	0.17	0.55	0.18	0.10
Average	**0.15**	**0.55**	**0.20**	**0.10**

The results obtained from the second round assessment (Table 8.3) are satisfactory and the average in degree of belief for each fuzzy expression is rounded as {0.15 *'very low'*, 0.55 *'low'*, 0.20 *'average'*, 0.10 *'high'*}.

The assessments for other first level criteria for both cost and technical performance follow the same procedure by the engineering design team. Safety estimates can be obtained using the fuzzy averaging method described in the previous chapter. The results generated are depicted as follows:

<u>Option #1:</u>

Safety (option #1) = {*0.205 'good', 0.241 'average', 0.261 'fair', 0.293 'poor'*}

Capital cost (option #1) = {*0.15 'very low', 0.55 'low', 0.2 'average', 0.1 'high'*}
Maintenance cost (option #1) = {*0.2 'very low', 0.3 'low', 0.35 'average', 0.15 'high'*}
Operational cost (option #1) = {*0.15 'very low', 0.2 'low', 0.3 'average', 0.35 'high'*}
Inspection cost (option #1) = {*0.05 'very low', 0.35 'low', 0.15 'average', 0.45 'high'*}

Reliability (option #1) = {*0 'very low', 0.15 'low', 0.25 'average', 0.6 'high'*}
System integration (option #1) = {*0.1 'very low', 0.25 'low', 0.3 'average', 0.35 'high'*}
Supportability (option #1) = {*0.1 'very low', 0.35 'low', 0.15 'average', 0.4 'high'*}

<u>Option #2:</u>

Safety (option #2) = {0.*501 'good', 0.171 'average', 0.197 'fair', 0.131 'poor'*}

Capital cost (option #2) = {*0 'very low', 0.25 'low', 0.3 'average', 0.45 'high'*}
Maintenance cost (option #2) = {*0.15 'very low', 0.15 'low', 0.25 'average', 0.45 'high'*}
Operational cost (option #2) = {*0.15 'very low', 0.2 'low', 0.35 'average', 0.3 'high'*}
Inspection cost (option #2) = {*0.1 'very low', 0.35 'low', 0.3 'average', 0.25 'high'*}

Reliability (option #2) = {*0 'very low', 0.05 'low', 0.15 'average', 0.8 'high'*}
System integration (option #2) = {*0.15 'very low', 0.25 'low', 0.25 'average', 0.35 'high'*}

Supportability (option #2) = {*0.1 'very low', 0.2 'low', 0.25 'average', 0.45 'high'*}

Option #3:

Safety (option #3) = {*0.437 'good', 0.112 'average', 0.352 'fair', 0.099 'poor'*}

Capital cost (option #3) = {*0.35 'very low', 0.45 'low', 0.2 'average', 0 'high'*}
Maintenance cost (option #3) = {*0.05 'very low', 0.15 'low', 0.35 'average', 0.45 'high'*}
Operational cost (option #3) = {*0.15 'very low', 0.15 'low', 0.25 'average', 0.45 'high'*}
Inspection cost (option #3) = {*0.05 'very low', 0.3 'low', 0.35 'average', 0.3 'high'*}

Reliability (option #3) = {*0 'very low', 0.05 'low', 0.2 'average', 0.75 'high'*}
System integration (option #3) = {*0.05 'very low', 0.15 'low', 0.25 'average', 0.55 'high'*}
Supportability (option #3) = {*0.1 'very low', 0.1 'low', 0.35 'average', 0.45 'high'*}

Option # 4:

Safety (option #4) = {*0.661 'good', 0.103 'average', 0.236 'fair', 0 'poor'*}

Capital cost (option #4) = {*0.1 'very low', 0.35 'low', 0.3 'average', 0.25 'high'*}
Maintenance cost (option #4) = {*0.05 'very low', 0.15 'low', 0.3 'average', 0.5 'high'*}
Operational cost (option #4) = {*0.05 'very low', 0.15 'low', 0.35 'average', 0.45 'high'*}
Inspection cost (option #4) = {*0.10 'very low', 0.15 'low', 0.25 'average', 0.5 'high'*}

Reliability (option #4) = {*0 'very low', 0.05 'low', 0.3 'average', 0.65 'high'*}
System integration (option #4) = {*0 'very low', 0.15 'low', 0.35 'average', 0.5 'high'*}
Supportability (option #4) = {*0.05 'very low', 0.15 'low', 0.35 'average', 0.45 'high'*}

These systems are to be evaluated and compared on the basis of safety, four basic cost-related criteria and three technical performance related criteria.

Step 4: Determine the relative weights of the criteria in the hierarchical structure and use IDS to synthesise all related basic criteria into second level criteria.

The weighting factors for each basic criterion (first level) and each second-level criterion are shown in Tables 8.4 and 8.5 respectively.

Table 8.4. Weighting factors for each basic criterion (first level).

Basic Criterion	Weighting factors
Safety	1
Capital	0.2
Maintenance	0.4
Operational	0.3
Inspection	0.1
Reliability	0.5
Integration	0.3
Supportability	0.2

Table 8.5. Weighting factors for second-level criterion.

Composite criterion	Weighting factors
Safety	0.6
Cost	0.3
Technical	0.1

The proposed design-decision support framework is used to determine which of the four options best satisfies the requirements of the project. The evaluation is to be conducted assuming that the reliability is 2.5 times as important to the evaluators as the supportability, and 1.7 times as important as the easy system integration. The capital cost is twice as important as inspection cost, maintenance cost is 4 times as important as inspection cost and twice as importance as capital cost, operational cost is 3 times as important as inspection cost. In the second level, safety is 6 times as important as technical performance, twice as important as cost. The cost is 3 times as important as technical performance. In addition, the evaluation criteria are only known approximately because the design of the system is still in the initial stages. Moreover there is a high level of uncertainty associated with these criteria.

The main window of IDS [Yang & Xu, 2004] for solving the design option problem is shown in Figure 8.3.

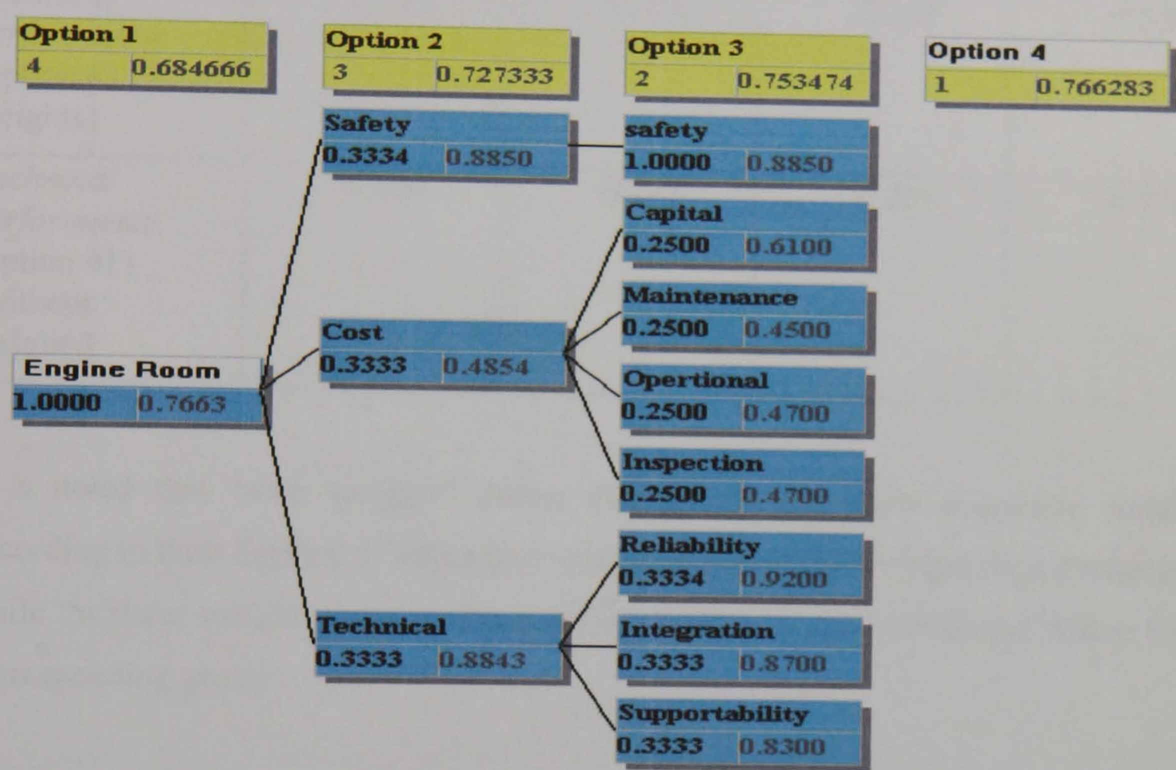


Figure 8.3. IDS main window for synthesis of safety, cost and technical performance not weighted.

The synthesis of the second level criteria of cost, safety and technical performance for the four options is shown as follows:

Option #1:

Safety expression	*'good'*	*'average'*	*'fair'*	*'poor'*
Safety (option #1)	*0.205*	*0.241*	*0.261*	*0.293*

Cost expression	*'very low'*	*'low'*	*'average'*	*'high'*
Cost (option #1) [with weights]	*0.157*	*0.328*	*0.295*	*0.220*
Cost (option #1) [without weights]	*0.129*	*0.363*	*0.248*	*0.260*

Technical performance	*'very low'*	*'low'*	*'average'*	*'high'*
Technical performance (option #1) [with weights]	*0.035*	*0.198*	*0.239*	*0.528*
Technical performance (option #1) [without weights]	*0.059*	*0.241*	*0.224*	*0.476*

It is noted that "with weights" means that criteria are given respective weights according to their degrees of importance assigned by experts during design evaluation, while "without weights" means that criteria are all of equal importance within their corresponding group.

Option #2:

Safety expression	*'good'*	*'average'*	*'fair'*	*'poor'*
Safety (option #2)	*0.501*	*0.171*	*0.197*	*0.131*

Cost expression	*'very low'*	*'low'*	*'average'*	*'high'*
Cost (option #2) [with weights]	*0.110*	*0.191*	*0.294*	*0.405*
Cost (option #2) [without weights]	*0.091*	*0.231*	*0.302*	*0.376*

Technical performance	*'very low'*	*'low'*	*'average'*	*'high'*
Technical performance (option #2) [with weights]	*0.046*	*0.112*	*0.179*	*0.663*
Technical performance (option #2) [without weights]	*0.073*	*0.151*	*0.203*	*0.573*

<u>Option #3:</u>

Safety expression	*'good'*	*'average'*	*'fair'*	*'poor'*
Safety (option #3)	*0.437*	*0.112*	*0.352*	*0.099*

Cost expression	*'very low'*	*'low'*	*'average'*	*'high'*
Cost (option #3) [with weights]	*0.124*	*0.211*	*0.298*	*0.367*
Cost (option #3) [without weights]	*0.141*	*0.263*	*0.294*	*0.302*

Technical performance	*'very low'*	*'low'*	*'average'*	*'high'*
Technical performance (option #3) [with weights]	*0.023*	*0.071*	*0.218*	*0.688*
Technical performance (option #3) [without weights]	*0.042*	*0.086*	*0.247*	*0.625*

<u>Option #4:</u>

Safety expression	*'good'*	*'average'*	*'fair'*	*'poor'*
Safety (option #4)	*0.661*	*0.103*	*0.236*	*0.000*

Cost expression	*'very low'*	*'low'*	*'average'*	*'high'*
Cost (option #4) [with weights]	*0.055*	*0.174*	*0.309*	*0.462*
Cost (option #4) [without weights]	*0.067*	*0.188*	*0.298*	*0.447*

Technical performance	*'very low'*	*'low'*	*'average'*	*'high'*
Technical performance (option #4) [with weights]	*0.006*	*0.079*	*0.309*	*0.606*
Technical performance (option #4) [without weights]	*0.014*	*0.101*	*0.322*	*0.563*

Step 5: Define a utility space to evaluate the different second level criteria on the same scale.

Safety, technical performance associated with and cost incurred for each design option are mapped onto the utility space and expressed in terms of utility expressions as shown in Table 8.6.

Table 8.6. Linguistic variables for utility expressions corresponding to cost, safety and technical performance expressions.

Utility expressions	**Safety expressions**	**Cost expressions**	**Technical performance expressions**
Greatly preferred	Good	Very low	High
Preferred	Average	Low	Average
Moderately preferred	Fair	Average	Low
Slightly preferred	Poor	High	Very low

Step 6: Perform system (engine room) synthesis for each design option using IDS.

This step involves the synthesis of the three second-level criteria on the same scale of a utility space. The system synthesis for each option is shown in Table 8.7.

Table 8.7. The results of system synthesis for each option.

	'Greatly preferred'	*'Preferred'*	*'Moderately preferred'*	*'Slightly preferred'*
Option #1				
with weights for both first and second levels criteria	*0.212*	*0.263*	*0.267*	*0.258*
without weights for both first and second levels criteria	*0.269*	*0.281*	*0.252*	*0.198*
Option #2				
with weights for both first and second levels criteria	*0.432*	*0.172*	*0.212*	*0.184*
without weights for both first and second levels criteria	*0.404*	*0.198*	*0.213*	*0.185*
Option #3				
with weights for both first and second levels criteria	*0.389*	*0.135*	*0.328*	*0.148*
without weights for both first and second levels criteria	*0.420*	*0.202*	*0.240*	*0.138*
Option #4				
with weights for both first and second levels criteria	*0.534*	*0.128*	*0.248*	*0.090*
without weights for both first and second levels criteria	*0.454*	*0.200*	*0.208*	*0.138*

Step 7: Compare the options by computing the preference estimate for each design option using IDS.

The results of the computed preference estimate for each design option are shown in Table 8.8, Figure 8.4 and Figure 8.5.

Table 8.8. Computed preference estimate for each design option.

Option	Preference estimate
Option # 1	
with weights for both first and second level criteria	0.634
Without weights for both first and second levels criteria	0.890
Option # 2	
with weights for both first and second level criteria	0.734
without weights for both first and second levels criteria	0.950
Option # 3	
with weights for both first and second level criteria	0.724
without weights for both first and second levels criteria	0.940
Option # 4	
with weights for both first and second level criteria	0.803
without weights for both first and second levels criteria	0.920

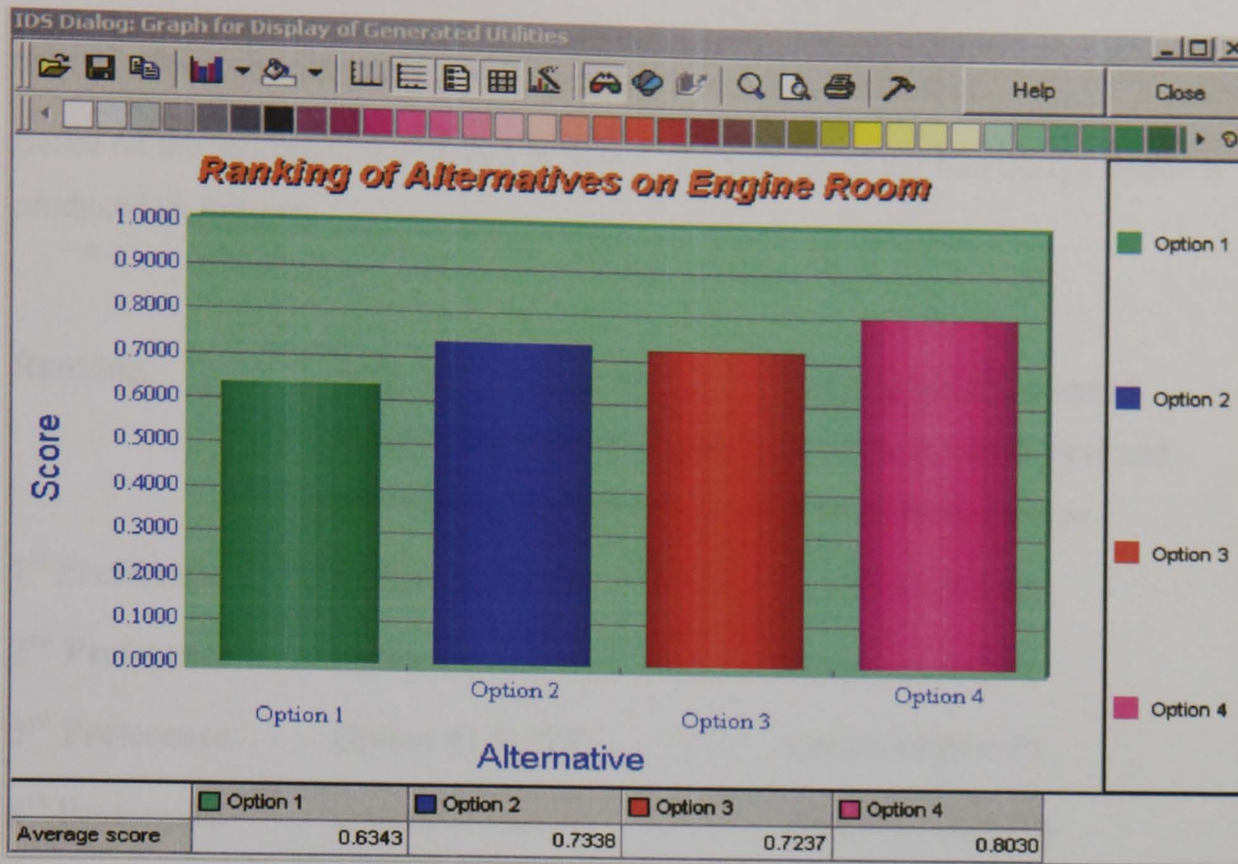


Figure 8.4. Performance estimates of the four design options (with weights for both first and second level criteria).

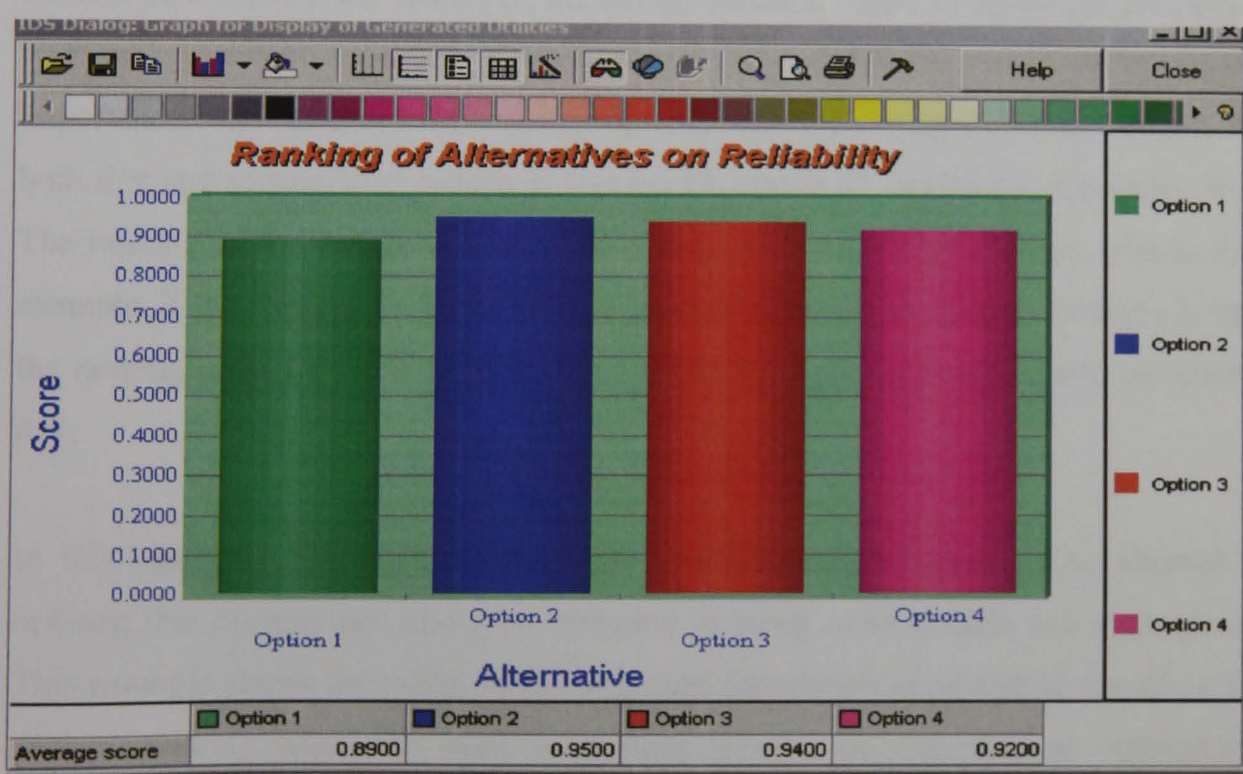


Figure 8.5. Performance estimates of the four design options (without weights for both first and second level criteria).

Step 8: Rank the alternative design options in order of preference.

Based on the information obtained in Step 7, the ranking of the four design option is produced as follows:

Ranking	**with involvement of weights for both first and second level criteria**	**without involvement of weights for both first and second level criteria**
1st Preference	Option #4 (0.803)	Option #2 (0.950)
2nd Preference	Option #2 (0.734)	Option #3 (0.940)
3rd Preference	Option #3 (0.724)	Option #4 (0.920)
4th Preference	Option #1 (0.634)	Option #1 ((0.890)

In this example the order of selection was not clear from the original range of data. This is often the case when decisions are made on the development of new systems without past experience. However, the design-decision support framework provides a systematic approach to making a selection when the criteria are vague and of varying importance. The ranking of the design options with the consideration of weights for both first and second level criteria is {option #4, option #2, option #3, and option #1}. The ranking of the design options may change with the weights of the criteria. For example, if the weights for both first and second level criteria are not considered, then the ranking order of the four options is {option #2, option #3, option #4, and option #1}.

In this example only eight criteria were used to compare among four alternative options; this process can easily be extended to many more criteria and alternatives. This example shows the utility of the proposed framework in providing a method for decision-making when the basic evaluating criteria are uncertain or information available is incomplete.

8.6 Conclusion

The chapter was performed to demonstrate the use of a design-decision support framework to assist in decision-making under conditions of vague or qualitative criteria of unequal importance. The proposed framework uses criteria that are subjective with a high level of uncertainty.

The suggested framework provides a powerful tool for comparing alternatives under subjective and uncertain evaluation procedures. In the evaluation process, the evaluating criteria or objectives are rated against each other, forcing the decision maker to decide what is most important to the final result. Most importantly, the process provides a result based on the degree to which each alternative meets each objective, thereby allowing for a decision based on factors that may have been overlooked in conventional procedures.

The final result (ranking of the design/procurement proposals) may vary with the weights assigned to each criterion and group. Thus, a sensitivity analysis may be required to investigate the effect for the weights. Because the selection of different basic criteria may also lead to different results, care must be taken to select all of the critical requirement criteria so that other criteria choices will not radically alter the result of the analysis.

References

Blockley, D. & Godfrey, P. (2001), "Doing It Differently", Thomas Telford, London, UK.

Dicky, J. & Watts, T. (1978), "Analytic Techniques in Urban and Regional Planning", McGraw-Hill, NY, USA.

Goldstein, N. (1975), "A Delphi on the Future of the Steel and Ferroalloy Industries, In the Delphi Techniques and Applications", Addison Wesley, Reading, pp.210-216, MA, USA.

Goldstein, N. (1992), "Modified Delphi: a Concept for New Product Forecasting", Journal of Business Forecasting, Vol 11, No 4, pp 10-11.

Klir, G. J. & Folger, T. A. (1988), "Fuzzy Sets, Uncertainty, and Information", Prentice-Hall, Eaglewood Cliffs, NJ, USA.

Linstone, H. & Turoff, M. (1975), "The Delphi Method: Techniques and Applications", Addison Wesley, Reading, pp 3-12, MA, USA.

Moller, B., Beer M., Graf, W. & Hoffmann, A. (1999), "Possibility Theory Based Safety Assessment", Computer-Aided Civil and Infrastructure Engineering, Vol 14, pp 81-91.

Robinson, J. B. L. (1991), "Delphi Technology for Economic Impact Assessment", Journal of Transportation Engineering, Vol 117, No 3.

Sii, H. S. & Wang, J. (2003), "A Design-Decision Support Framework for Evaluation of Design Options/Proposals Using a Composite Structure Methodology Based on The Approximate Reasoning Approach and The Evidential Reasoning Method, IMechE Journal of Process Mechanical Engineering, Vol 217, pp 59-76.

Terano, T., Asai, K. & Sugeno, M. (1997), "Applied Fuzzy Systems", AP Professional, NY, USA.

Wang, J., Yang, J. B. & Sen, P. (1996), "Multi-Person and Multi-Attribute Design Evaluations Using Evidential Reasoning Based on Subjective Cost Analysis", Reliability Engineering & System Safety, Vol 52, No 2, pp 113-129.

Yang, J. B. (2001), "Rule and Utility Based Evidential Reasoning Approach for Multi-Attribute Decision Analysis under Uncertainties", European Journal of Operational Research, Vol 131, No 1, pp 31-61.

Yang, J. B. & Xu, D. L. (2002), "On the Evidential Reasoning Algorithm for Multiple Attribute Decision Analysis under Uncertainty", IEEE Transaction of Systems, Man, and Cybernetics – Part A: System and Humans, Vol 32, No 3, pp 289-304.

Yang, J. B. & Xu, D. L. (2004), "Intelligent Decision System via Evidential Reasoning", IDSL, Cheshire, UK.

Zadeh, L. (1965), "Fuzzy Sets", Information and Control, Vol 8, pp 338-353.

Zimmermann, H. J. (1991), "Fuzzy Set Theory and Its Applications", Kluwer-Nijhoff Publishing, Hingham, Massachusetts, USA.

CHAPTER 9 - DECISION MAKING USING ANALYTICAL HIERARCHY PROCESSING TO FIRE SAFETY ASSESSMENT OF A PASSENGER SHIP

Summary

An approach to integrate fire safety assessment and decision-making using the Analytical Hierarchy Processing (AHP) method is described. The aim of this approach is to reduce the occurrence probability and severity of fire during the operational phase of a passenger vessel. It utilises AHP theory to rank the impacts of fires and further integrates the available control options (to minimise these fires) within the analysis. The result obtained from the analysis reflects the most favoured control option that will address the possible fires within the ship to a satisfactory level. A test case, which considers the operation of a passenger vessel, is used to demonstrate the described approach.

9.1 Introduction

In the last 15 years there have been some severe fire accidents with passenger vessels, such as Scandinavian Star tragedy of April 1990 with 158 deaths and Moby Prince disaster of April 1991 with 140 fatalities. The accidents have demonstrated a clear need for fire safety improvements.

The development of a fire from ignition to a major flammable incident usually takes a very short time. The speed of combustion is dependent on many factors such as oxygen, fuel, weather conditions, etc. Fire at sea, can have more serious and dramatic implications than a land based fire. On seagoing passenger vessels fire could develop quicker due to materials of construction, fuels, chemicals, petroleum gases, or other hazardous cargoes, which are indigenous to ships and contained within a relatively small area [Haisley, 1997].

The application of fire safety engineering principles allows a more coherent, systematic and holistic approach to be used to address fire safety in passenger ship design. Consequently, it is inevitable that specific expertise is required and that more data and paperwork are to be generated, with direct impact on both designers and administrations.

9.2 Statistics and Fire Safety Assessment of a Passenger Ship

The Lloyd's Register (LR) ship casualty database contains details of any reported fires and explosions that occur on LR classed vessels. In the majority of cases the actual raw data is obtained directly from the surveyors in the field, via the classification reporting system. Press articles and casualty returns, reported in Lloyd's List and similar publications are scanned as a secondary source of information [Mather & Strang, 1997].

The following research criteria limits were applied to highlight passenger ship fires by searching the LR ship casualty database [Mather & Strang, 1997]:

1. Fires.
   The database search was limited to fires. Only if an explosion was followed by a fire does the incidence of the explosion result in an entry in the data.

2. Passenger vessels built between 1 January 1982 and 31 December 1996.
   The range of dates was chosen to provide a large enough sample of vessels and ensured that the analysis was carried out on fires where the vessels were constructed to current fire safety standards.

From the data obtained from the LR ship casualty database, Table 9.1 has been complied. Table 9.1 lists the recorded fires and gives specific details of the locations of the fire and where known the extinguishing used.

Table 9.1. Reports of fires.

Passenger Vessels		
Total recorded fires		9 ships
Ship motion	Under way	6
	Port	1
	Anchored	0
	New construction	2
Location of fire outbreaks	Accommodation	2
	Galley	1
	Machinery space / pump room	5
	Electrical installations	1
	Funnels and uptakes	0
	Stores	0
	Oil tanks	0
	Cargo space	0
	Deck area	0
Heat source	Electrical	1
	Spontaneous combustion	0
	Hot surface	5
	Scavenge space	0
	Repairs / cutting / welding	1
	Cigarette / match	1
	Cargo / coal	0
	Outside the ship	0
Heat source contributory factor	Negligence	0
	Collision	0
	Sabotage	1
	Soot deposits	1
	Fuel oil / leakage oil	1
	Allowed to burn	0
	Fixed water – main / sprinkler	1
	Fixed gas	2
	Fixed foam	0

Fire extinguishing	Fixed dry powder	0
	Portable water	1
	Portable gas	0
	Portable foam	1
	Portable dry powder	1
Fire containment	Additional help	2
	Spread	1
Loss of life/injuries	Loss of life	0
	Serious injury	0
Degree	Major / serious	1
	Sank at sea	0
	Temporarily disabled	2

9.2.1 Accommodation zone

In accommodation superstructures, it is sometimes found that all combustible materials have been consumed leaving no identifiable patterns of fire spread, particularly in older ships in which bulkheads are largely combustible.

Accommodation superstructures are divided into compartments designed to resist the spread of fire from one to another. Factors affecting the speed with which a fire develops in an accommodation should be identified. Open stairwells provide a route by which fire may spread rapidly from one deck to another. Enclosed stairways are fitted with self closing doors and a careful note of the condition of hinges and smoke patterns on the door edges and jambs may assist in determining whether these doors were open or closed at the time of the fire [Foster & Burgoyne, 1997].

Fire may be communicated from one deck to another or from one compartment to another on the same deck, by heat conduction through a steel barrier (i.e. deckhead or bulkhead). The speed with which a fire may develop in an adjacent compartment will be dependent upon the nature of the combustible material which is in contact with surface of the division on the opposite side of the existing fire. Sometimes a smouldering fire may be initiated in the adjacent compartment and sometimes can elapse before transition to flame occurs. Therefore, the nature and disposition of the combustible contents in the adjacent compartment will determine the rate at which the fire develops there. In this way, the fire may spread gradually or quickly through an accommodation superstructure depending on the prevailing conditions [Foster & Burgoyne, 1997].

In accommodation spaces, good housekeeping and common-sense are important in preventing fires from occurring and spreading. Crew members should use cooking facilities in a pantry with care, especially during night watches. Smoke detectors and heat detectors should be maintained in good working order and fire doors should be kept closed, especially in stairwell areas [Foster & Burgoyne, 1997].

Clearly the accommodation has a higher fire risk; it is where personnel are concentrated owing to work and recreational activities, including smoking. Additionally, there are many combustible materials in these spaces. However, because the accommodation is a manned area, detection and extinction of a fire is usually quickly dealt with, thus preventing any escalation of a fire [Mather & Strang, 1997].

9.2.2 Public area

There was one reported fire in a galley. However, because the galley is manned when the main hazard is present, during cooking, any fire is quickly detected and extinguished. Also the public areas (i.e. shopping malls, restaurants, cinemas) are well equipped with fire extinguishing facilities [Mather & Strang, 1997].

9.2.3 Machinery space

The data analysis clearly indicates that the areas where the most fires can be expected are the machinery spaces, despite the numerous fire safety measures provided in these spaces.

The most common cause of fire in the machinery spaces is due to the contact of oil on the hot surfaces of machinery. The fuel can be lubricating oil, diesel or fuel oil at high or low pressure. There are regulatory requirements for high pressure fuel lines to be sheathed or armoured. Most of the engine room fires are the result of low pressure or lubricating oil leaks. The sources are rarely the line itself, but usually the joints or filters. Frequently, the problem is poor access so that engineers working on routine maintenance or repair work inadvertently trigger a fire [Waite, 2000].

A glib response would be that these problems are crew negligence. Even if that was the case, it does not relieve the designer from the responsibility to attempt to anticipate the circumstances under which fire could occur. Apart from the obvious armouring or sheathing of all oil lines, they should be fitted with quick response low pressure cut off. A fire may then start, but not continue to be fuel fed. Also, fuel lines which run over machinery or adjacent machinery where atomisation may occur should have limited lengths to limit the volume of fuel that can spray onto the engine [Waite, 2000].

Engine room fires also have a tendency to extend to the accommodation. The rules and requirements are designed to provide time to prevent the spread of fire. The principle is to either contain the fire to give time to fight it effectively or to give time to evacuate the ship if it gets out of control. Clearly, there is no guarantee nor can there be, to stop the fire completely within a space. It is inevitable, therefore, that machinery fires can spread to the accommodation so that abandonment is necessary [Waite, 2000].

9.2.4 Evacuation

The evacuation process of a passenger vessel may be divided into the following phases: Mustering, Embarkation and Evacuation.

When the captain decides to muster the passengers, the alarm will be activated and announcements will inform passengers and crew about the situation. The passengers are guided to leave their cabins and walk along the marked escape-ways to their muster areas, where the crew will support them. If the situation deteriorates, embarkation of the lifeboats, which in the meantime have been swung out by crew, will be started. The lifeboats will normally be sequentially launched.

Some of the crew will systematically search the cabins and others will be posted at strategic positions to guide passengers to their muster stations. The crew members shall be dressed in their uniforms to be perceived as authority persons by the passengers. This contributes to preventing inappropriate or dysfunctional behaviour among passengers. Otherwise, they may adopt the behaviour of other persons appearing to behave with authority who in the worst case may be panicking people.

In case of a severe accident on a passenger vessel, the captain is responsible for deciding whether the ship has to be evacuated. The history shows that several examples that delay to take a decision or incorrect decisions have contributed to creating disasters. On the other hand, premature evacuations may also cause loss of lives.

9.2.5 Analytical Hierarchy Processing (AHP) for fire safety assessment and decision-making for passenger ships

Quantification of the fire safety provision in new passenger ships is very difficult. In the retrofitting of existing vessels much of the work associated with fire safety is executed as an operation without the predetermination of the ships most at risk and a priority ranking of the components which contribute to the achievement of the required level of fire safety. Several spaces to quantify fire safety have been reviewed in Sections 9.2.1 - 9.2.4 and also investigated in the previous chapters 4 – 8.

The use of the AHP method enables the solutions for each area with possible fire identified, to be integrated within the analysis. The solutions to reduce the risk levels (posed by fires) 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.

9.3 Analytical Hierarchy Processing (AHP)

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 25 years ago by Dr. Thomas Saaty [Saaty, 1980], and continues to be a highly regarded and widely used decision-making theory.

AHP is especially suitable for complex decisions, which involve the comparison of decision elements that are difficult to quantify. 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 & Kangas, 1997], [Braunschweig, 2000], industrial engineering applications [Alidi, 1996], [Bhattarai & Fujiwara, 1997] and financial applications [Hachadorian, 1987]. The application of AHP theory to ascertain business and financial risk has been relatively popular in the past [Jensen, 1987a-b], [Nezhad, 1988], [Simkin et al., 1990]. It has also found its place in risk and safety assessment of engineering systems [Shields & Silcock, 1986], [Saaty, 1987], [Hamalainen & Karjalainen, 1989, 1992], [Shields et al., 1990], [Frank, 1995], [Pillay, 2001].

9.3.1 Background of AHP

In AHP, the quantified judgements on pairs of activities C_i and C_j are represented by an n-by-n matrix.

$A = (a_{ij})$ where $i, j = 1, 2, \dots, n.$ (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:

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

where each a_{ij} is the relative importance of activity i to activity j. Having recorded the quantified judgements of comparisons on pair (C_i, C_j) as numerical entry 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 [Pillay & Wang, 2003]. 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.

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, the equation for calculating w_1 is shown below:

$$w_1 = \frac{1}{n}\left[\left(\frac{a_{11}}{\sum_{i=1}^{n} a_{i1}}\right) + \left(\frac{a_{12}}{\sum_{i=1}^{n} a_{i2}}\right) + \dots \left(\frac{a_{1n}}{\sum_{i=1}^{n} a_{in}}\right)\right] \quad (3)$$

In general, weights w_1, w_2, w_3, ..., w_n can be calculated using the following equation [Pillay & Wang, 2003]:

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}}\right) (k = 1, \ldots\ldots n) \qquad (4)$$

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

Generally, if pairwise comparisons are provided for three or more criteria, they may not be completely consistent and as such it is not straightforward to obtain relative weights of criteria from the comparisons. The AHP method and several other methods can be used to generate weights using pairwise comparisons.

9.3.2 Risk and AHP

Risks are by nature subjective, therefore, the AHP method may be suited for risk assessment in many situations. 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 [Pillay, 2001].

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, 1988].

9.4 Application of AHP to a Passenger Vessel Operation

The flowchart in Figure 9.1 illustrates the steps involved in carrying out the application of AHP to a passenger vessel operation.

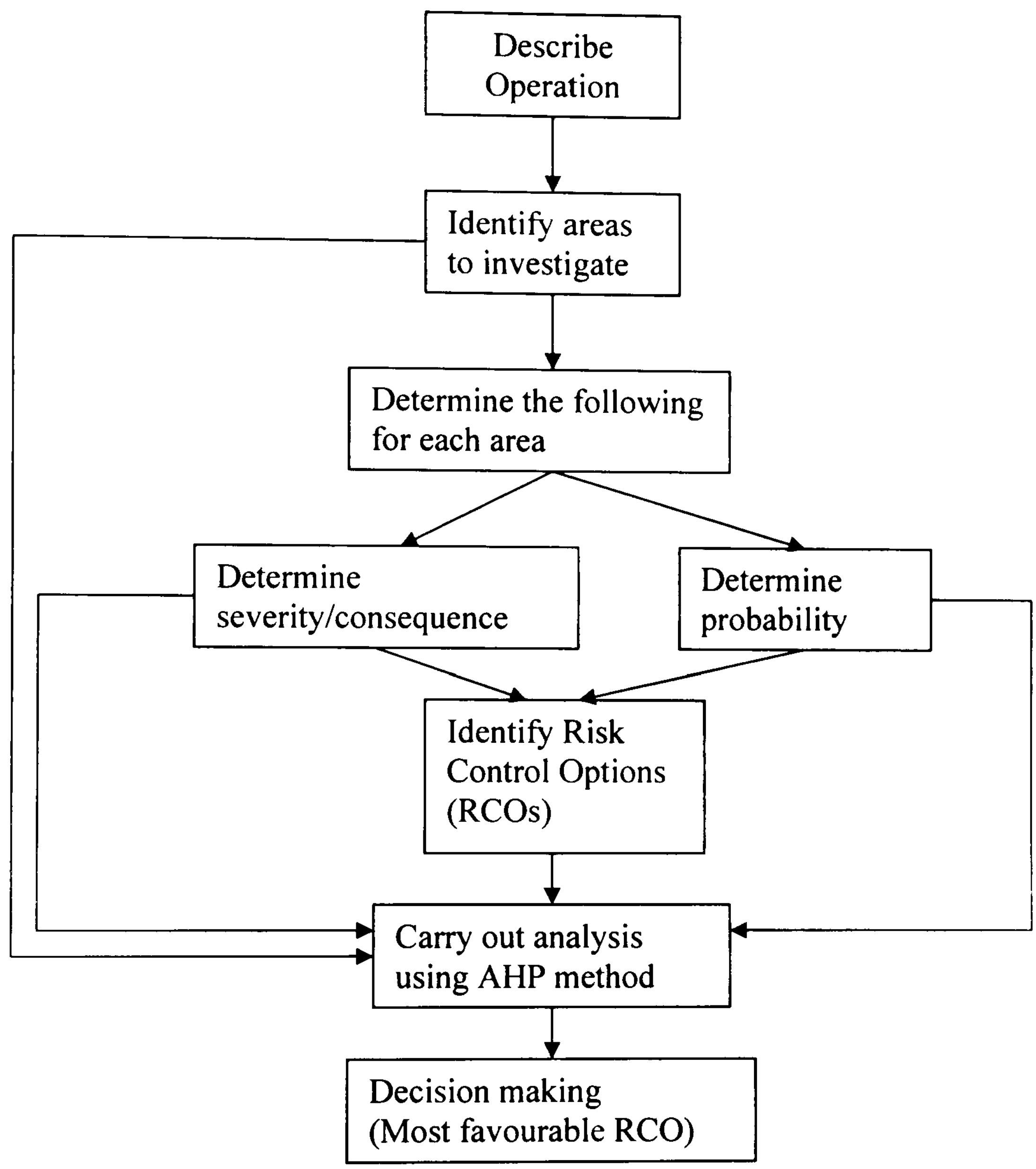


Figure 9.1. Flowchart of the approach.

This approach can be executed in the following seven distinct steps:

Step 1. Describe operation - The operation under consideration is described in detail, highlighting all the areas that will be investigated to achieve the desired objective of the defined operation.

Step 2. Identify areas to be investigated - Identify all areas that are to be investigated to achieve the objective of the operation.

Step 3. Determine the following for each area - For each of the areas identified in Step 2.

Step 4. Determine the probability of occurrence - Using the LR ship database, determine the probability that a fire might occur while investigating out the area specified in Step 2.

Step 5. Determine the severity of possible consequence.

Step 6. Determine Risk Control Options (RCOs) - Considering the operation under study, determine several options that could address the risks estimated (associated with each area defined in Step 2).

Step 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 the risks associated with areas where fire could manifest.

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

(i) 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.

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

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

(iv) Evaluation - The final solution ratings are then calculated using the ratings determined in *(iii)* and the weighting vector calculated in step *(ii)*.

9.5 Case Study

The purpose of this analysis is to address the high risk areas of fire occurrence during the passenger ship operation.

9.5.1 Hierarchy set-up

The hierarchy fire safety operation can be represented diagrammatically as shown in Figure 9.2. The elements in level two are set to be the probability of a fire occurring and its the severity. The sub-elements (level three) are determined by grouping the whole area into public area, accommodation zone and machinery space. Each area investigated in relation to the whole is considered within this level i.e. cabin, bathroom, corridor, etc.

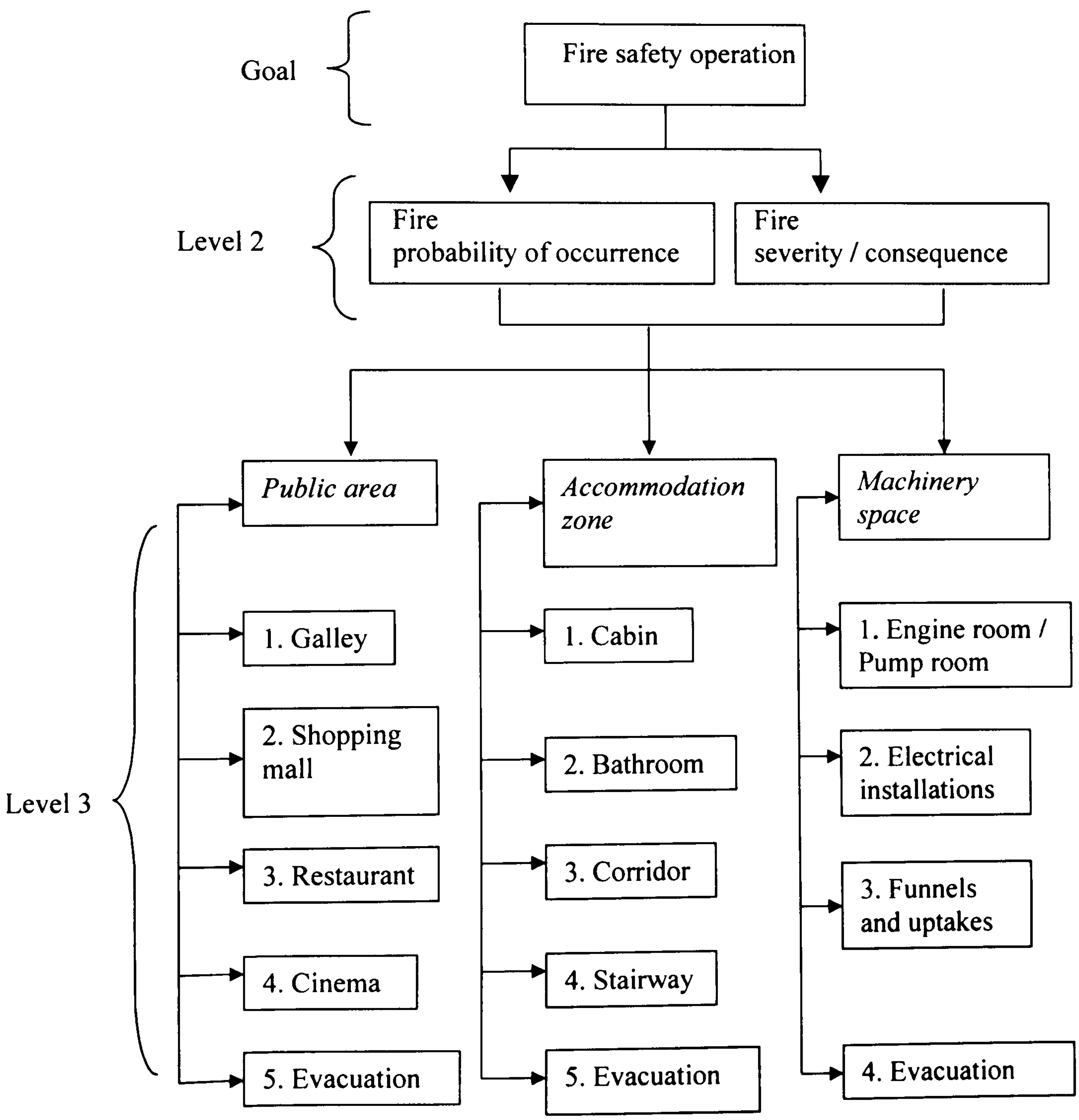


Figure 9.2. Fire safety operation and its hierarchical levels.

9.5.2 Level two matrix

Occurrence probability and severity make up the two elements in Level 2 as seen in Figure 9.2. These two elements are compared against each other to determine the weighting vector of each element. Considering the goal of the analysis, it is decided that both these elements are equally important to a fire safety assessment, hence, the Level 2 matrix is determined as:

$$LevelTwo = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}, \text{ and the } Weighting\,Vector = \begin{bmatrix} 1/(1+1) = 0.5 \\ 1/(1+1) = 0.5 \end{bmatrix}$$

The first column in the level two matrix, (1, 1) is normalised so that the sum of the entries is 1.0. The weighting of Element 1 will be given as 1/(1+1) = 0.5 or 50%. Similarly Elements 2 can be calculated to be 50%. The normalised weighting vector for Elements 1 and 2 is [0.5 0.5]. The sum of all two weightings is 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 so that their total weight will equal that of the previous level (level two). For example, for Element 1, sub-elements public area, accommodation zone and machinery space will be given a total weight of 50%. 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 solutions 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 fire 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 for 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) [Pillay & Wang, 2003].

9.5.3 Fire probability evaluation

First, the importance of each element (public area, accommodation zone or machinery space) is determined. Considering the recorded fires from Table 9.1 and assuming with Table 9.2 that machinery space is moderately more important than accommodation zone and absolutely more important than public area. Then the level two matrix may be represented as seen in the matrix below:

Table 9.2. Comparison scale.

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

Public area: 1 fire (From Table 9.1) probability (From Table 9.2): 1

Accommodation zone: 2 fires probability: 5

Machinery space: 6 fires probability: 9

$$\textbf{\textit{Probability}} = \begin{bmatrix} 1.0000 & 5.0000 & 9.0000 \\ 1/5 = 0.2000 & 5/5 = 1.0000 & 9/5 = 1.8000 \\ 1/9 = 0.1111 & 5/9 = 0.5556 & 9/9 = 1.0000 \end{bmatrix}$$

The weighting vector is obtained as follows:

$$\textit{Weighting vector} = \begin{bmatrix} 1/(1.0000 + 0.2000 + 0.1111) = 0.7627 \\ 1/(5.0000 + 1.0000 + 0.5556) = 0.1525 \\ 1/(9.0000 + 1.8000 + 0.5556) = 0.0848 \end{bmatrix}$$

The normalised vector is determined by considering the weighting vector at level two as follows:

$$\textit{Normalised vector} = \begin{bmatrix} 0.7627 \times 0.5 = 0.3814 \\ 0.0763 \\ 0.0424 \end{bmatrix}$$

The probability of fire is considered for each of the areas investigated. Using Table 9.1 and Table 9.2, each area is assigned the fire probability. This data is then used to compare each area against the others to determine the level three matrices. The matrices for the probability of occurrence for each area are determined as follows:

$$\textit{Public area} = \begin{bmatrix} 1.0000 & 0.2000 & 1.0000 & 0.3333 & 5.0000 \\ 5.0000 & 1.0000 & 5.0000 & 1.6665 & 25.0000 \\ 1.0000 & 0.2000 & 1.0000 & 0.3333 & 5.0000 \\ 3.0000 & 0.6001 & 3.0000 & 1.0000 & 15.0000 \\ 0.2000 & 0.0400 & 0.2000 & 0.0667 & 1.0000 \end{bmatrix}$$

$$\textit{Weighting vector} = \begin{bmatrix} 0.0980 \\ 0.4902 \\ 0.0980 \\ 0.2942 \\ 0.0196 \end{bmatrix}, \textit{Normalised vector} = \begin{bmatrix} 0.0980 \times 0.3814 = 0.0374 \\ 0.1869 \\ 0.0374 \\ 0.1122 \\ 0.0075 \end{bmatrix}$$

$$Accommodation\ zone = \begin{bmatrix} 1.0000 & 1.0000 & 1.0000 & 1.0000 & 7.0000 \\ 1.0000 & 1.0000 & 1.0000 & 1.0000 & 7.0000 \\ 1.0000 & 1.0000 & 1.0000 & 1.0000 & 7.0000 \\ 1.0000 & 1.0000 & 1.0000 & 1.0000 & 7.0000 \\ 0.1429 & 0.1429 & 0.1429 & 0.1429 & 1.0000 \end{bmatrix}$$

$$Weighting\ vector = \begin{bmatrix} 0.2414 \\ 0.2414 \\ 0.2414 \\ 0.2414 \\ 0.0344 \end{bmatrix}, Normalised\ vector = \begin{bmatrix} 0.2414 \times 0.0763 = 0.0184 \\ 0.0184 \\ 0.0184 \\ 0.0184 \\ 0.0026 \end{bmatrix}$$

$$Machinery\ space = \begin{bmatrix} 1.0000 & 0.2000 & 0.2000 & 3.0000 \\ 5.0000 & 1.0000 & 1.0000 & 15.0000 \\ 5.0000 & 1.0000 & 1.0000 & 15.0000 \\ 0.3333 & 0.0667 & 0.0667 & 1.0000 \end{bmatrix}$$

$$Weighting\ vector = \begin{bmatrix} 0.0882 \\ 0.4412 \\ 0.4412 \\ 0.0294 \end{bmatrix}, Normalised\ vector = \begin{bmatrix} 0.0882 \times 0.0424 = 0.0037 \\ 0.0187 \\ 0.0187 \\ 0.0013 \end{bmatrix}$$

9.5.4 Fire severity evaluation

The importance of each element (public area, accommodation zone or machinery space) is determined using the comparison scale in Table 9.2, the data in Table 9.1 and expert judgement. The matrix below is obtained for the severity importance of each element.

$$\boldsymbol{Severity} = \begin{bmatrix} 1.0000 & 5.0000 & 9.0000 \\ 0.2000 & 1.0000 & 1.8000 \\ 0.1111 & 0.5556 & 1.0000 \end{bmatrix}$$

The weighting vector is obtained as follows:

$$Weighting\ vector = \begin{bmatrix} 0.7627 \\ 0.1525 \\ 0.0848 \end{bmatrix}$$

The normalised vector is determined by considering the weighting vector at level two as follows:

$$Normalised\ vector = \begin{bmatrix} 0.7627 \times 0.5 = 0.3814 \\ 0.0763 \\ 0.0424 \end{bmatrix}$$

The matrices for the severity of the consequences of fire for each area at level three are determined as follows:

$$Public\ area = \begin{bmatrix} 1.0000 & 1/5 = 0.2000 & 1/3 = 0.3333 & 1/9 = 0.1111 & 5.0000 \\ 5.0000 & 1.0000 & 1.6665 & 0.5555 & 25.0000 \\ 3.0000 & 0.6000 & 1.0000 & 0.3333 & 15.0000 \\ 9.0000 & 1.8000 & 3.0000 & 1.0000 & 45.0000 \\ 0.2000 & 0.0400 & 0.0667 & 0.0222 & 1.0000 \end{bmatrix}$$

$$Weighting\ vector = \begin{bmatrix} 0.0549 \\ 0.2748 \\ 0.1648 \\ 0.4945 \\ 0.0110 \end{bmatrix},\ Normalised\ vector = \begin{bmatrix} 0.0549 \times 0.3814 = 0.0209 \\ 0.1048 \\ 0.0629 \\ 0.1886 \\ 0.0042 \end{bmatrix}$$

$$Accommodation\ zone = \begin{bmatrix} 1.0000 & 0.3333 & 0.2000 & 0.1429 & 5.0000 \\ 3.0000 & 1.0000 & 0.6000 & 0.4287 & 15.0000 \\ 5.0000 & 1.6665 & 1.0000 & 0.7145 & 25.0000 \\ 7.0000 & 2.3324 & 1.3996 & 1.0000 & 35.0000 \\ 0.2000 & 0.0667 & 0.0400 & 0.0286 & 1.0000 \end{bmatrix}$$

$$Weighting\ vector = \begin{bmatrix} 0.0617 \\ 0.1853 \\ 0.3087 \\ 0.4320 \\ 0.0123 \end{bmatrix}, Normalised\ vector = \begin{bmatrix} 0.0617 \times 0.0763 = 0.0047 \\ 0.0141 \\ 0.0236 \\ 0.0330 \\ 0.0009 \end{bmatrix}$$

$$Machinery\ space = \begin{bmatrix} 1.0000 & 0.1111 & 0.3333 & 1.0000 \\ 9.0000 & 1.0000 & 3.0000 & 9.0000 \\ 3.0000 & 0.3333 & 1.0000 & 3.0000 \\ 1.0000 & 0.1111 & 0.3333 & 1.0000 \end{bmatrix}$$

$$Weighting\ vector = \begin{bmatrix} 0.0714 \\ 0.6429 \\ 0.2143 \\ 0.0714 \end{bmatrix}, Normalised\ vector = \begin{bmatrix} 0.0714 \times 0.0424 = 0.0030 \\ 0.0273 \\ 0.0091 \\ 0.0030 \end{bmatrix}$$

9.5.5 Risk Control Options (RCO)s

Several viable Risk Control Options (RCO)s are generated in order to reduce the level of risks posed by fires during the operation. These risk control options are evaluated for their effectiveness against each of the areas identified. For this example, an arbitrary scale (1 to 10) is used to compare the RCOs, 1 being not effective and 10 being most effective. Six RCOs have been identified to reduce the probability and severity of fire in the operation. These RCOs include:

RCO 1 – Training of crew.

RCO 2 – Reduce ignition sources.

RCO 3 – Maintenance work.

RCO 4 – Heat removal.

RCO 5 – Additional crewing.

RCO 6 – Quick fire detection and confirmation

(audio and visual alarms, TV monitoring, indications, etc.).

The matrices for the effectiveness of each RCO in reducing the probability of fire occurrence in the accommodation zone are presented in the form as seen in Table 9.3. Similarly all other areas are compared with the different RCOs in terms of reduction in the probability of fire occurrence and its possible consequences.

Table 9.3. RCOs matrix.

Accommodation zone	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5	RCO 6
Cabin	3	6	5	4	2	9
Bathroom	2	5	6	6	2	8
Corridor	5	6	7	8	7	9
Stairway	6	5	8	8	9	9
Evacuation	9	6	8	8	9	9

9.5.6 RCOs Evaluation to reduce probability of occurrence

The matrix for the effectiveness of each RCO in reducing the probability of fire occurrence in the public area is formulated as follows:

$$\textit{Public area} = \begin{bmatrix} 9 & 9 & 8 & 8 & 6 & 9 \\ 8 & 9 & 7 & 8 & 9 & 9 \\ 9 & 9 & 8 & 9 & 8 & 9 \\ 9 & 9 & 8 & 8 & 8 & 9 \\ 9 & 8 & 8 & 9 & 9 & 9 \end{bmatrix} \quad \textit{Normalised vector} = \begin{bmatrix} 0.0374 \\ 0.1869 \\ 0.0374 \\ 0.1122 \\ 0.0075 \end{bmatrix}$$

Then the normalised results are obtained as follows:

$$\textit{Normalised results} = \begin{bmatrix} 0.0069 & 0.0069 & 0.0061 & 0.0061 & 0.0046 & 0.0069 \\ 0.0299 & 0.0336 & 0.0262 & 0.0299 & 0.0336 & 0.0336 \\ 0.0065 & 0.0065 & 0.0058 & 0.0065 & 0.0058 & 0.0065 \\ 0.0198 & 0.0198 & 0.0176 & 0.0176 & 0.0176 & 0.0198 \\ 0.0013 & 0.0012 & 0.0012 & 0.0013 & 0.0013 & 0.0013 \end{bmatrix}$$

In the above matrix, the first column of the first row means that RCO1 value is normalised so that it will be given as 9/(9+9+8+8+6+9) = 0.1837 × 0.0374 = 0.0069. In a similar way, the normalised matrices for the effectiveness of each RCO in reducing the probability of fire occurrence in the accommodation zone and machinery space are formulated as follows:

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

$$Normalised\ results = \begin{bmatrix} 0.0019 & 0.0038 & 0.0032 & 0.0025 & 0.0013 & 0.0057 \\ 0.0013 & 0.0032 & 0.0038 & 0.0038 & 0.0013 & 0.0051 \\ 0.0022 & 0.0026 & 0.0031 & 0.0035 & 0.0031 & 0.0039 \\ 0.0025 & 0.0020 & 0.0033 & 0.0033 & 0.0037 & 0.0037 \\ 0.0005 & 0.0003 & 0.0004 & 0.0004 & 0.0005 & 0.0005 \end{bmatrix}$$

$$Machinery\ space = \begin{bmatrix} 9 & 9 & 9 & 9 & 9 & 9 \\ 8 & 8 & 7 & 8 & 6 & 9 \\ 6 & 7 & 8 & 7 & 6 & 8 \\ 5 & 7 & 8 & 7 & 8 & 9 \end{bmatrix}$$

$$Normalised\ results = \begin{bmatrix} 0.0006 & 0.0006 & 0.0006 & 0.0006 & 0.0006 & 0.0006 \\ 0.0033 & 0.0033 & 0.0028 & 0.0033 & 0.0024 & 0.0037 \\ 0.0027 & 0.0031 & 0.0036 & 0.0031 & 0.0027 & 0.0036 \\ 0.0001 & 0.0002 & 0.0002 & 0.0002 & 0.0002 & 0.0003 \end{bmatrix}$$

9.5.7 RCOs Evaluation to reduce severity of possible consequences

The normalised matrices for the effectiveness in reducing the severity of possible consequences in the public area, accommodation zone and machinery space are formulated as follows:

$$Public\ area = \begin{bmatrix} 9 & 8 & 7 & 9 & 9 & 9 \\ 7 & 8 & 7 & 9 & 6 & 8 \\ 9 & 9 & 8 & 8 & 7 & 9 \\ 8 & 8 & 7 & 9 & 7 & 9 \\ 9 & 9 & 8 & 8 & 7 & 9 \end{bmatrix}$$

$$Normalised\ results = \begin{bmatrix} 0.0037 & 0.0033 & 0.0029 & 0.0037 & 0.0037 & 0.0037 \\ 0.0163 & 0.0186 & 0.0163 & 0.0210 & 0.0140 & 0.0186 \\ 0.0113 & 0.0113 & 0.0101 & 0.0101 & 0.0088 & 0.0113 \\ 0.0314 & 0.0314 & 0.0275 & 0.0354 & 0.0275 & 0.0354 \\ 0.0008 & 0.0008 & 0.0007 & 0.0007 & 0.0006 & 0.0008 \end{bmatrix}$$

$$Accommodation\ zone = \begin{bmatrix} 7 & 8 & 6 & 7 & 6 & 9 \\ 5 & 6 & 7 & 8 & 4 & 8 \\ 6 & 7 & 6 & 7 & 5 & 8 \\ 7 & 6 & 8 & 8 & 7 & 9 \\ 9 & 8 & 8 & 9 & 9 & 9 \end{bmatrix}$$

$$Normalised\ results = \begin{bmatrix} 0.0008 & 0.0009 & 0.0007 & 0.0008 & 0.0007 & 0.0010 \\ 0.0019 & 0.0022 & 0.0026 & 0.0030 & 0.0015 & 0.0030 \\ 0.0036 & 0.0042 & 0.0036 & 0.0042 & 0.0030 & 0.0048 \\ 0.0051 & 0.0044 & 0.0059 & 0.0059 & 0.0051 & 0.0066 \\ 0.0002 & 0.0001 & 0.0001 & 0.0002 & 0.0002 & 0.0002 \end{bmatrix}$$

$$Machinery\ space = \begin{bmatrix} 9 & 9 & 8 & 8 & 7 & 9 \\ 6 & 7 & 5 & 6 & 6 & 8 \\ 5 & 4 & 6 & 6 & 7 & 8 \\ 6 & 8 & 7 & 8 & 7 & 9 \end{bmatrix}$$

$$Normalised\ results = \begin{bmatrix} 0.0005 & 0.0005 & 0.0005 & 0.0005 & 0.0004 & 0.0005 \\ 0.0043 & 0.0050 & 0.0036 & 0.0043 & 0.0043 & 0.0058 \\ 0.0013 & 0.0010 & 0.0015 & 0.0015 & 0.0018 & 0.0020 \\ 0.0004 & 0.0005 & 0.0005 & 0.0005 & 0.0005 & 0.0006 \end{bmatrix}$$

9.5.8 Results

The results obtained from Sections 9.5.6 and 9.5.7 are collated to determine the best RCO. Tables 9.4 and 9.5 show the summary of these results obtained in percentage.

Table 9.4. Summary of results for probability element.

	Public area	Accommodation zone	Machinery space	Total rating
RCO 1	*6.44%*	*0.84%*	*0.67%*	***7.95%***
RCO 2	*6.80%*	*1.19%*	*0.72%*	***8.71%***
RCO 3	*5.69%*	*1.38%*	*0.72%*	***7.79%***
RCO 4	*6.14%*	*1.35%*	*0.72%*	***8.21%***
RCO 5	*6.29%*	*0.99%*	*0.59%*	***7.87%***
RCO 6	*6.81%*	*1.89%*	*0.82%*	***9.52%***

Table 9.5. Summary of results for severity element.

	Public area	Accommodation zone	Machinery space	Total rating
RCO 1	*6.35%*	*1.16%*	*0.65%*	***8.16%***
RCO 2	*6.54%*	*1.18%*	*0.70%*	***8.42%***
RCO 3	*5.75%*	*1.29%*	*0.61%*	***7.65%***
RCO 4	*7.09%*	*1.41%*	*0.68%*	***9.18%***
RCO 5	*5.46%*	*1.05%*	*0.70%*	***7.21%***
RCO 6	*6.98%*	*1.56%*	*0.89%*	***9.43%***

For example, the score for RCO 6 in the category of the public area in Table 9.4 is 0.0069 + 0.0336 + 0.0065 + 0.0198 + 0.0013 = 0.0681 =6.81%. This represents the effectiveness of RCO 6 to reduce the probability of fire occurring when the vessel is operated. In Table 9.5, the same principles are applied for the evaluation of the effectiveness of each RCO to reduce or mitigate the possible consequences of fire occurring when the ship is operated.

Each of these tables (Tables 9.4 and 9.5) 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 these tables for the respective RCOs. Table 9.6 shows the final results obtained for this analysis.

Table 9.6. Final ranking of RCOs.

	Public area	Accommodation zone	Machinery space	Total rating
RCO 1	*12.79%*	*2.00%*	*1.32%*	***16.11%***
RCO 2	*13.34%*	*2.37%*	*1.42%*	***17.13%***
RCO 3	*11.44%*	*2.67%*	*1.33%*	***15.44%***
RCO 4	*13.23%*	*2.76%*	*1.40%*	***17.39%***
RCO 5	*11.75%*	*2.04%*	*1.29%*	***15.08%***
RCO 6	*13.79%*	*3.45%*	*1.71%*	***18.95%***

From Table 9.6, it can be determined that the best control option to reduce the probability of occurrence and the severity of fire during the operation is RCO 6. The results entail that by installing various warning and indication devices onto/for the equipment used for the operation on a passenger vessel, the level of fire risk can be reduced most effectively. The ranking order of the RCO in terms of effectiveness is {RCO 6, RCO 4, RCO, 2, RCO 1, RCO 3 and RCO 5}. The ranking of the RCOs may change with the weights.

9.6 Conclusion

Fire remains a great hazard to life at sea and there have been very serious incidents of ship fires over the past. The rules and regulations primarily require fire safety for high risk areas such as machinery spaces to be protected by structural fire resisting divisions, detection and extinguishing systems. Furthermore, the importance of human actions is not generally considered in the standards, although this aspect will be addressed to a certain extent by the code.

Many uncertainties exist in fire safety assessment, e.g., the level of fire safety achieved by compliance with existing prescriptive fire safety legislation. The AHP can be used for analysing and prioritizing the effect of uncertainty and identifying the uncertainties that influence outcomes more than others.

The suggested framework provides powerful tools for comparing alternatives under subjective and uncertain evaluation procedures. The chapter was performed to demonstrate the use of a design-decision support framework based on the AHP methodology to assist in decision-making. The approach can be used to identify risk control options and also determine the best one for reducing fire hazards.

In this chapter, only fires are considered in the analysis. However, this can be extended to include failures induced by other causes, such as collision or flooding.

References

Alho, J. M. & Kangas, J. (1997), "Analysing Uncertainties in Experts' Opinions of Forest Plan Performance", Forest Science, Vol 43, No 4, pp 521-528.

Alidi, A. S. (1996), "Use of the Analytic Hierarchy Process to Measure the Initial Viability of Industrial Projects", International Journal of Project Management, Vol 14, No 4, pp 205-208.

Bhattarai, S. & Fujiwara, O. (1997), "Evaluation of Appropriate Scale of Hydropower Development for Nepal: an Analytic Hierarchy Process Approach", Proceeding of International Conference on Large Scale Water Resources Development in Developing Countries: New Dimensions of Problems and Prospects, Kathmandu, Nepal, 20-24 October.

Braunschweig, T. (2000), "Priority Setting in Agricultural Biotechnology Research: Supporting Public Decisions in Developing Countries with the Analytic Hierarchy Process", ISNAR Research Report No 16, International Service for National Agricultural Research, Hague, Netherlands.

Foster, C. D. & Burgoyne, J. H. (1997), "Scientific Investigation of Marine Shipping Fires and Explosions", Proceeding of International Conference on Fire at Sea, The RINA, London, UK, 20-21 November.

Frank, M. V. (1995), "Choosing Among Safety Improvement Strategies: a Discussion with Example of Risk Assessment and Multi-Criteria Decision Approaches for NASA", Reliability Engineering & Systems Safety, Vol 49, No 3, pp 311-324.

Hachadorian, G. E. (1987), "Hierarchical Determination of the Risk of Forced Divestment to Foreign Owned Enterprises in LDC's", Mathematical Modelling Vol 8, pp 163-166.

Haisley, J. (1997), "Escape Route Protection Nozzles for Seagoing Vessels", Proceeding of International Conference on Fire at Sea, The RINA, London, UK, 20-21 November.

Hamalainen, R. P. & Karjalainen, R. (1989), "Structuring the Risks of Energy Production", Proc. of the International Conference on Multicriteria Decision-Making, pp 677-689, Bangkok, Thailand, 6-8 December.

Hamalainen, R. P. & Karjalainen, R. (1992), "Decision Support for Risk Analysis in Energy Policy", European Journal of Operational Research, Vol 56, No 2, pp 172-183.

Jensen, R. E. (1987a), "International Investment Risk Analysis: Extensions for Multinational Corporation Capital Budgeting Models", Mathematical Modelling, Vol 9, No 3, pp 265-284.

Jensen, R. E. (1987b), "A Dynamic Analytic Hierarchy Process Analysis of Capital Budgeting under Stochastic Inflation Rates, Risk Premiums, Liquidity Preferences: Theory", Advances in Financial Planning and Forecasting, Vol 2, pp 269-302.

Mather, P. & Strang, T. D. (1997), "Regulatory Requirements – Do These Adequately Reflect Actual Fire Experience?", Proceeding of International Conference on Fire at Sea, The RINA, London, UK, 20-21 November.

Nezhad, H. G. (1988), "Risk Assessment for International Investment", Reprints of the International Symposium on the Analytic Hierarchy Process, Sept. 6-9, pp 371-380, Tianjin University, Tianjin, China.

Pillay, A. (2001), "Formal Safety Assessment of Fishing Vessels", PhD Thesis, School of Engineering, Liverpool John Moores University, UK.

Pillay, A. & Wang, J. (2003), "Technology and Safety of Marine Systems", Elsevier (Ocean Engineering Book Series), ISBN: 0080441483, Linacre House Jordan Hill, Oxford, UK.

Saaty, T. L. (1980), "The Analytic Hierarchy Process", McGraw Hill Company, NY, USA.

Saaty, T. L. (1987), "Risk - Its Priority and Probability: the Analytic Hierarchy Process", Risk Analysis, Vol 7, No 2, pp 159-172.

Saaty, T. L. (1988), "The Analytic Hierarchy Process" University of Pittsburgh, USA.

Shields, T. J. & Silcock, G. (1986), "Application of the Hierarchical Approach to Fire Safety", Fire Safety Journal, Vol 11, No 3, pp 235-242.

Shields, T. J., Silcock, G. & Donegan, H. A. (1990), "Towards the Development of a Fire Safety Systems Evaluation for Public Assembly Buildings", Construction Management and Economics, Vol 8, No 2, pp 147-158.

Simkin, M. G., Bagranoff, N. A. & Crawford P. J. (1990), "Using a Decision Support System to Manage Exchange Rate Risk", Oklahoma Business Bulletin, Vol 58, No 3, pp 32-35.

Waite, J. (2000), "Feeding Accident Experience into Design", IMarEST International International Conference on Safety of Large Passenger Ships – Looking to the Future, Vol 112, Part 2, London, UK, 15-16 May.

CHAPTER 10 – CONCLUSIONS AND FURTHER WORK

Summary

This chapter concludes the thesis by summarising the results of the research project carried out by the author and outlining the contributions of the fire safety analysis methodologies developed for passenger ships. The areas where further effort and research are required to refine the developed methodologies are also reviewed. Finally, other important safety features related to fire safety assessment are briefly discussed.

10.1 Conclusions

10.1.1 Discussion of the main aim

The chapters of this thesis have thoroughly described the series of work covered in the research project. The research started with the review of the development of fire safety and reliability assessment techniques in the maritime industry. This is followed by a comprehensive statistical study on casualty or failure data on passenger vessels. The basic concept of the fire safety assessment approach and its application to the passenger ships are discussed. The Formal Safety Assessment (FSA) proposed by the UK Maritime Coastguard Agency (MCA) as a means to improve the safety of international shipping is outlined. A range of novel fire safety analysis methodologies has been developed and the reasons behind the development of such methodologies have been explained.

The main aim of this research was to analyse fire issue concerning the passenger vessel sector of the shipping industry. All the fire safety analysis methodologies described in this thesis have been developed in a generic sense and theoretically they are, in principle, applicable to all designs of maritime engineering products and projects.

10.1.2 Evaluation of main objectives

The first objective (identification of fire safety techniques) has been identified and investigated. Accident investigations over the years have provided valuable information for fire safety assessment of passenger vessels. Lessons learnt from previous accidents have been used as a guide to produce rules and regulations to prevent similar accidents from happening. The various databases available concerning these accidents and many more within the maritime industry are discussed. 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. From the data analysis (Chapter 2), there is an urgent need to address the fire safety issues plaguing the passenger vessel industry. In order to analyse the fire safety issues, typical analysis techniques can be employed. These are described in Chapter 3. The review of these typical analysis methods has been carried out, highlighting the advantages and limitations of each method. These methods can be broadly divided into two categories, namely, quantitative and qualitative analysis.

The second objective (study the FSA) of this thesis has been examined in Chapter 3. The third objective (development novel fire safety assessment) was to develop techniques and decision support approaches for fire safety assessment. These novel methods capable of performing fire risk quantification and risk ranking are presented in Chapters 4, 5, 7 and 8.

The fourth objective (development of a suitable model) was achieved through Chapters 6 and 9 where a suitable model was developed to assist in fire safety implementation. A method using Analytical Hierarchy Processing (AHP) is proposed in Chapter 9 to select the most favourable Risk Control Option (RCO). 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 collision and feasibility of implementation. The evacuation modelling methodology proposed in Chapter 6 provides guidance in appraising capital projects relating to passenger ships. The fifth objective (identification of further research areas) is discussed in Chapter 10.2.

10.1.3 Discussion on effectiveness of this project

The main aim was generally achieved but not to the extent that it was expected. This was due to some difficulties. It was difficult to compare the real or test data and results with industry due to the lack of access and confidentiality policy of companies. Another negative aspect is that the information gathered from other researchers used in the development of fire and evacuation modelling techniques was limited.

One of the major limitations of the fire safety analysis methodologies developed in this thesis is that they require intensive computational effort in conducting fire safety assessment, especially for maritime systems with a high level of complexity. It is rather a time consuming task to learn and familiarise with such methodologies in order to use them in fire safety assessment, however, advancement of computing and man-machine interfacing technologies of the present time may resolve such problems.

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.

It is 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.

10.1.4 Definitive conclusion

It is believed that the approaches and safety based decision-making techniques developed in this thesis have great potential as effective aids and alternatives in the areas of fire safety assessment. They will gain increased usage in the various stages of maritime system design and operations. It is also emphasised that a close collaboration with maritime industry is essential in promoting the practical applications of these methodologies, especially with organisations dealing with safety related problems with a high level of uncertainty as well as a lacking of safety and reliability data. This will provide a positive ground and chance for the applications of such methodologies to become established in order to prove their feasibility and practicality, otherwise, it is more likely that their full potential will not be realised.

10.2 Further Work

10.2.1 Recommendation for further research

There are several areas that may be worthwhile exploring and exploiting on the basis of the methodologies developed in this thesis. These can be summarised by the points presented below:

- The confidence and effectiveness of the FSA approach is greatly dependent on the reliability of system's failure/incident data. The quantitative risk assessments in the FSA approach were required to access some detailed, reliable and consistent incident, casualty or failure databases related to the system under scrutiny, such as a generic passenger vessel. The availability of these data sources is one of the major limitations of this study, as the data required for quantitative assessment is either unavailable or insufficient. As noted by [Dobler, 1994], at present IMO and the governments of its member countries have to rely on the statistical information collated and published by private sources, or, they have recourse on a contractual basis to the databases maintained by these sources, if more details are required. It is hoped that the application of FSA may trigger the Flag States and Classification Societies to collect data on operational experience, which can be very handy for effective precaution risk analysis in the future. Furthermore, human reliability data associated with maritime tasks is also a paramount area needed to be focused as the availability of these data can be useful to conduct human error analysis since human factors are considered to be one of the major contributors to maritime incidents.

- Rules and regulation governing passenger 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 procedures, 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, the development of rules applied to passenger ship using the formal fire safety assessment methods needs to be researched and explored.

- Formal training and education programmes should be developed for crew and passengers. This programme should not only highlight fire safety matters, but also extend to cover competency issues. Such a programme will be a starting point to cultivate a safety culture within the passenger ship industry. The outcome of the formal fire safety analysis can be used to identify areas where such training and education are lacking and the programme can be developed addressing these areas.

- Quantitative risk assessment of passenger 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 vessel. 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 fire 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, & Kumar, 2001].

- The decision making framework presented in Chapter 9 is inevitably a computationally intensive method, however, the proposed algorithm could be easily programmed and will definitely offer a convenient tool to evaluate option selection in decision making.

- Safety, cost and reliability may need to be considered simultaneously in an integrated manner in various design process of a maritime system. One can fully make use of the advancement in theory and applications of control engineering to establish quantitative models for synthesising safety, cost and reliability in a generic safety assessment framework. This generic framework will look very similar to the safety models proposed in Chapter 8, but with more comprehensive evaluation and further incorporation with cost and reliability models in order to minimise risk, minimise cost and maximise reliability in system optimisation study.

- In recent years, in order to reduce human error and to provide operators with a improved working environment in maritime applications, advanced in computer technology have been increasingly used to substitute control tasks which were used to be performed by human operators. This inevitably has led to the development of more software intensive systems. However, the employment of software in control systems has introduced new failure modes and created problems in the development of safety-critical systems. In maritime system design, every safety-critical system in the software domain requires a thorough investigation to ensure it is extremely unlikely for its behaviour to lead to a catastrophic failure with catastrophic consequences. This is also to provide evidence that the risk associated with the software is acceptable within the overall system risks.

10.2.2 Other important safety features

Other important safety features related to the fire safety analysis methodologies developed in this research project are described as follows:

- For the past century the marine industry has used prescriptive rules and regulations for treating safety matters. If a change of approach is to be adopted, the major hurdles to be overcome will need to be identified and possible solutions suggested. The shift to more goal-setting regulations may encourage engineers and designers to consider safety related issues more explicitly while carrying out design optimisation studies.

- As life safety is a prime concern in the passenger ship industry, more effort should be devoted to the life saving at sea in an attempt to estimate and evaluate the associated risks more reliably and effectively.

- The passenger vessel companies should work together with the aim of improving the safety culture in and around passenger ships. The human element can be addressed in a holistic manner and not just by addressing a few areas that fall within the competence of the IMO, such as training, prevention of pollution and ship management [IMO, 1994]. Since safety is dominated by human factors, the development of a positive safety culture is the only way to improve the standard of safety. The analysis of accidents across different industries frequently points to human error as being the cause in anything up to 80% of cases [Stansfeld, 1994], [Pomeroy, 1998]. To ensure that there is a safety culture within an organisation it is essential to develop a positive attitude to safety. The only effective way of achieving this is through education and training. This is a long term process and it requires significant resources. Human error is now receiving increasing attention, particularly from industries concerned with design and use of maritime and other high-tech engineering systems.

Fire safety is a complex subject and it involves management, engineering and operation underpinned by human factors. Therefore, in order to deal with safety one must have a proper understanding of all four aspects and competence in handling them.

References

Dobler, J. P. (1994), "The Requirement for the Publication of Detailed Global Marine Casualty Statistics", Marine Policy & Management, Vol 21, No 1, January.

IMO (1994), "International Safety Management Code (ISM Code)", IMO publication, London, UK.

Pomeroy, R. V. (1998), "Classification – Adapting and Evolving to Meet the Challenges of the New Safety Culture", IMarEST Conference on New Safety Culture, London, UK, 4 December.

Stansfeld, J. T. (1994), "The Safety Case", Lloyd's Register Technical Association (LRTA) No 3, Session 1994-95, London, UK.

Vosburg, J. & Kumar, A. (2001), "Managing Dirty Data in Organisations Using ERP: Lessons from a Case Study", Industrial Management and Data Systems, Vol 101, No 1, pp 21-31.

APPENDIX

Poster Presentation, Refereed Papers Published and Waiting to be Published

1. Wang, J., Saajedi, A., Pillay, A., Sii, H. S., Lois, P. & ***Kim, S. W.***, "Marine and Offshore Technology Research at Liverpool John Moores University", Poster Presentation, Presented in the UK Universities for North Sea Hydrocarbons Seminar and Workshop, Aberdeen Robert Gordon University, UK, 30 November-1 December, 2000.

2. Wang, J., Yang, J. B., Sii, H. S., Pillay, A. & ***Kim, S. W.***, "Marine and Offshore Risk Assessment and Control Engineering", Proceeding of the Annual Conference of Chinese Automation and Computer Society in the UK (CACSUK 2000), ISBN: 0 9533890 2 2, Loughborough, UK, 23 September, 2000.

3. Wang, J., Maistralis, E., Sii, H. S., ***Kim, S. W.***, Wong, C., Kwon, Y. S. & Jung, G. M., "Novel Risk Assessment Techniques and Their Application to Formal Safety Assessment of Ships", Proceeding of the 5th International Conference on Reliability, Maintainability & Safety, Dalian, P. R. China, 27-31 August, 2001.

4. ***Kim, S. W.***, Wang, J., Sii, H. S., Kwon, Y. S. & Jung, G. M., "Fire Safety Assessment on Passenger Ships: Application to an Accommodation Zone", Proceeding of the New S-Tech 2002 (In APMC – Asia Pacific Maritime Congress), Kobe, Japan, pp 271-282, 21-23 May, 2002.

5. ***Kim, S. W.***, Wang, J., Kwon, Y. S. & Wall, A., "Developments in Smoke Control System for Passenger Ships: Application to an Accommodation Zone", Proceeding of the 8th Chinese Automation & Computer Society Conference in the UK 2002 (CACSUK 2002), ISBN: 0 9533890 5 7, UMIST, Manchester, UK, pp 1-6, 20-21 September, 2002.

6. ***Kim, S. W.***, Kim, H. S., Wang, J., Wall, A. & Kwon, Y. S., "Evacuation Analysis of Passenger Ships: Using Computer Simulation to Predict Evacuation Performance", Asia Pacific Symposium on Safety (APSS) 2003, Taipei, Taiwan, 18-20 November, 2003.

7. ***Kim, S. W.***, Kim, H. S., Wang, J., Wall, A. & Kwon, Y. S., "Evacuation Analysis of Passenger Ships: Using Computer Simulation to Predict Evacuation Performance", International Journal of Safety, Vol 2, No 2, pp 17-21, 2003.

8. ***Kim, S. W.***, Kwon, Y. S., Wall, A. & Wang, J., "Fire Risk Modelling of Machinery Space: An Application of Approximate Reasoning Approach (Fuzzy Averaging Method) in Passenger Ship Engine Room", The 15th International Offshore and Polar Engineering Conference & Exhibition, Seoul, Korea, 19-24 June, 2005.