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The current status and future aspects in formal ship safety assessment

J. Wang *

School of Engineering, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK

Abstract

Formal ship safety assessment is a new approach that has attracted great attention in the marine industry over the last several years. In this paper, following a brief review of the current status of maritime safety assessment, a formal ship safety assessment framework is presented. The five steps in formal ship safety assessment are then briefly discussed. This is followed by the study of risk criteria in ship safety assessment and the discussion of its possible application in ship design and operation. The recommendations on further work required are finally given. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Safety case regimes have been used by high technology industries for many years, and have been recently adopted by the UK offshore industry following the public inquiry into the Piper Alpha accident of 6 July 1988 which caused 167 deaths (Department of Energy, 1990). In response to the accepted findings of the Piper Alpha inquiry the UK Health and Safety Executive (HSE) Offshore Safety Division launched a review of all offshore safety legislation and implemented changes. The changes sought to replace legislation which was seen as prescriptive with a more "goal-setting" regime. The mainstay of the regulations is the health and safety at work act. Under that act, a draft of the offshore installations (safety case) regulations was produced in 1992. It was then modified, taking into account comments arising from public consultation. The regulations came into force in 1993 (Offshore Installation (Safety Case) Regulations, 1992).

* Tel.: +44-151-231-2445; fax: +44-151-231-2453.
E-mail address: j.wang@livjm.ac.uk (J. Wang).

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An offshore safety case should include sufficient particulars to demonstrate that hazards with potential to cause major accidents have been identified, risks have been evaluated and measures have been taken to reduce them to As Low As Reasonably Practicable (ALARP) (Department of Energy, 1990). Offshore operators must submit safety cases for all existing and new offshore installations to the Offshore Safety Division of the HSE for acceptance. An installation cannot legally operate without an accepted operational safety case. The submitted safety cases may be studied by looking at accident scenarios and the assessment of the consequences of each scenario together with steps taken to control risks. To be acceptable a safety case must show that all hazards with the potential to produce a major accident have been identified and that associated risks are below a tolerability limit and have been reduced ALARP. For example, the occurrence likelihood of events causing a loss of integrity of the safety refuge should be less than 10^{-3} per platform year (Spouse, 1997) and associated risks should be reduced to ALARP. "The offshore installations and wells (design and construction, etc.) regulations" (DCR) were subsequently introduced. From the earliest stages of the installations and wells' life cycle operators must ensure that all safety-critical elements in both the software and system domains be assessed (DCR, 1996). The DCR allow offshore operators to have more flexibility to tackle their own offshore safety problems subject to a verification scheme. Offshore operators may use various safety assessment approaches and safety-based decision-making tools to study all safety-critical elements of offshore installations and wells to optimise safety. Recently, the industrial guidelines on a framework for risk-related decision support have been produced by the UKOOA (1999). In general, the framework could be usefully applied to a wide range of situations. Its aim is to support major decisions made during the design, operation and abandonment of offshore installations. It can also be combined with other formal decision-making aids such as Multi-Attribute Utility Analysis, Analytical Hierarchy Process or decision trees if a more detailed or quantitative analysis of the various decision alternatives is desired.

The main feature of the new offshore safety regulations in the UK is the absence of a prescriptive regime, defining specific duties of the operator and definition as regard to what are adequate means. This is in recognition of the fact that hazards related to an installation are specific to its function and site conditions.

In the shipping industry, recently, several serious accidents including the capsize of the *Herald of Free Enterprise*, the *Exxon Valdes* tragedy, the capsize of the *Estonia* and the grounding of the *Sea Empress*, have happened. These accidents have shocked the public and attracted great attention to ship safety. The studies on how similar accidents may be prevented have been actively carried out at both national and international levels. The adoption of the safety case approach in the UK offshore industry also encouraged marine safety analysts to look at the possibility of employing a similar "goal-setting" regime in the marine industry. In 1992 Lord Carver's report into ship safety raised the issue of a more scientific approach to the subject and recommended that emphasis be given to a performance-based regulatory approach (House of Lords, 1992). That was the initial idea of formal ship safety assessment. In some respects, such as class requirements for bulk carrier hull integrity, it has been happening. The current statutory safety regulations that govern ship safety at both national and international levels are prescriptive in nature and may not reflect the requirements of individual types of ship. Marine safety may be significantly improved by introducing a formal "goal-setting" safety assessment approach so that the challenge of new technologies and their application to ship design operation may be dealt with properly.

This paper will review the current status of formal ship safety assessment. The risk criteria and possible application areas of formal safety assessment will also be briefly studied.

2. Current status of formal ship safety assessment

As serious concern is raised over the safety of ships all over the world, the International Maritime Organisation (IMO) has continuously dealt with safety problems in the context of operation, management, survey, ship registration and the role of administration. The improvement of safety at sea has been highly stressed. The international safety-related marine regulations have been governed by serious marine accidents that have happened. The lessons were first learnt from the accidents and then the regulations and rules were produced to prevent similar accidents from occuring. For example, the capsize of the *Herald of Free Enterprise* in 1987 greatly affected the rule developing activities of the IMO (Cowley, 1995; Sekimizu, 1997). The accident certainly raised serious questions on operation requirements and the role of management, and stimulated discussions in those areas at the IMO. This finally resulted in the adoption of the International Safety Management (ISM) Code. The *Exxon Valdes* accident in 1989 seriously damaged the environment by the large-scale oil spill. It resulted in the international convention on Oil Pollution Preparedness, Response and Co-operation being established in 1990. Double hull or mid-deck structural requirements for new and existing oil tankers were subsequently applied (Sekimizu, 1997). The *Scandinavian Star* disaster in 1990 resulted in the loss of 158 lives. Furthermore, the catastrophic disaster of the *Estonia*, which capsized in the Baltic Sea in September 1994, caused more than 900 people to lose their lives. Those accidents highlighted the role of human error in marine casualties and, as a result, the new Standards for Training, Certificates and Watchkeeping for seafarers were subsequently introduced.

After Lord Carver's report on the investigation of the capsize of the *Herald of Free Enterprise* was published in 1992, the UK Maritime and Coastguard Agency (MCA: previously named as Marine Safety Agency) quickly responded and in 1993 proposed to the IMO that formal safety assessment should be applied to ships to ensure a strategic oversight of safety and pollution prevention. The UK MCA also proposed that the IMO should explore the concept of formal safety assessment and introduce formal safety assessment in relation to ship design and operation. The IMO reacted favourably to the UK's formal safety assessment submission. Since then, substantial work including demonstrating its practicability by a trial application to the safety of high speed catamaran ferries and a trial application to the safety of bulk carriers, has been done by the UK MCA. In the area of formal safety assessment, the UK is a leading nation where the MCA has played a very important role in promoting the use of formal ship safety assessment. In general, for the last several years the application of formal safety assessment has reached an advanced stage.

Safety assessment in ship design and operation may offer great potential incentives. The application of it may:

1. improve the performance of the current fleet, be able to measure the performance change and ensure that new ships are good designs;
2. ensure that experience from the field is used in the current fleet and that any lessons learned are incorporated into new ships; and
3. provide a mechanism for predicting and controlling the most likely scenarios that could result in incidents.

The possible benefits have already been realised by many shipping companies. For example, the P&O Cruises Ltd. in the UK has reviewed the implementation of risk assurance methods as a strategic project and proposed short-/medium-term and long-term objectives (Vie and Stemp, 1997). Its short-/medium-term objectives are: to provide a reference point for all future risk assurance work; to develop a structure chart that completely describes vessel operation; to complete a meaningful hazard identification as the foundation of the data set; to enable identification of realistic options for vessel improvement; to be a justified record of modifications adopted or rejected; and to be capable of incorporating and recording field experience to ensure that the knowledge is not lost. Its long-term objectives are: to provide a mechanism for understanding the effect of modifications on total vessel performance; to be capable of future development; to provide a basis for total valuation of identified improvements using cost-benefit analysis; to generate a meaningful risk profile for vessel operation; and to provide a monitor for evaluation of modification effectiveness. The idea of formal safety assessment may well be fitted to the above objectives in order to improve the company's performance.

3. Formal ship safety assessment

Formal safety assessment is a new approach to maritime safety which involves using the techniques of risk and cost-benefit assessment to assist in the decision-making process. It should be noted that there is a significant difference between the safety case approach and formal safety assessment. A safety case approach is applied to a particular ship, whereas formal safety assessment is designed to be applied to safety issues common to a ship type (such as high-speed passenger vessel) or to a particular hazard (such as fire). The philosophy of formal safety assessment is essentially the same as that of the safety case approach. Many ship owners have begun to develop their own ship safety cases. The major difference between such ship-specific applications of the approach and its generic application by regulators is that whilst features specific to a particular ship cannot be taken into account in a generic application, the commonalities and common factors which influence risk and its reduction can be identified and reflected in the regulator's approach for all ships of that type (IME/MCA, 1998). This should result in a more rational and transparent regulatory regime. Use of formal safety assessment by an individual owner for an individual ship on the one hand and by the regulator for deriving the appropriate regulatory requirements on the other hand, are entirely consistent (IME/MCA, 1998).

It has been noted that many leading classification societies including Lloyds Register of Shipping and American Bureau of Shipping are moving towards a risk-based regime. It is believed that the framework of formal safety assessment can facilitate such a move.

A formal ship safety assessment framework that has been proposed by the UK MCA consists of the following five steps:

1. the identification of hazards;
2. the assessment of risks associated with those hazards;
3. ways of managing the risks identified;
4. cost-benefit assessment of the options; and
5. decisions on which options to select

The above framework was initially studied at the IMO Maritime Safety Committee (MSC) meeting 62 in May 1993. At the 65th meeting of the MSC in May 1995, strong support was received from the member countries and a decision was taken to make formal safety assessment a high priority item on the MSC's agenda. Accordingly, the UK decided to embark on a major series of research projects to further develop an appropriate framework and conduct a trial application on the chosen subject of high speed passenger catamaran ferries. The framework produced was delivered to MSC 66 in May 1996, with the trial application programmed for delivery to MSC 68 in May 1997. An international formal safety assessment working group was formulated at MSC 66 and MSC 67 where draft international guidelines were generated, including all key elements of the formal safety assessment framework developed by the UK.

The IMO is likely to adopt key elements of risk-based and formal safety assessment schemes within its major review of Chapter II-2 of the 1974 SOLAS (Safety Of Life At Sea) Convention. Formal safety assessment involves much more scientific aspects than previous conventions. The benefits of adopting formal safety assessment as a regulatory tool include (MSA, 1993, p. 1):

1. a consistent regulatory regime which addresses all aspects of safety in an integrated way;
2. cost effectiveness, whereby safety investment is targeted where it will achieve the greatest benefit;
3. a pro-active approach, enabling hazards that have not yet given rise to accidents to be properly considered;
4. confidence that regulatory requirements are in proportion to the severity of the risks; and

5. a rational basis for addressing new risks posed by ever-changing marine technology.

3.1. Identification of hazards

This step aims at identifying and generating a selected list of hazards specific to the problem under review. In formal ship safety assessment, a hazard is defined as, "a physical situation with potential for human injury, damage to property, damage to the environment or some combination" (MSA, 1993, p. 10). Hazard identification is concerned with using "brainstorming" technique involving trained and experienced personnel to determine the hazards. An accident is defined as "a status of the vessel, at the stage where it becomes a reportable incident which has the potential to progress to loss of life, major environmental damage and/or loss of the vessel" (MSA, 1993). The accident categories include: (1) contact or collision; (2) explosion; (3) external hazards; (4) fire; (5) flooding; (6) grounding or stranding; (7) hazardous substances; (8) loss of hull integrity; (9) machinery failure; and (10) loading and unloading related failure. Human error issues should be systematically dealt with in the formal safety assessment framework. Significant risks can be chosen in this step by screening all the identified risks. Various scientific safety assessment approaches such as Preliminary Hazard Analysis, Failure Mode, Effects and Criticality Analysis, and HAZard and OPerability study, can be applied in this step.

3.2. Assessment of risks

This step aims at assessing risks and factors influencing the level of safety. Risk assessment involves studying how hazardous events or states develop and interact to cause an accident. Shipping consists of a sequence of distinct phases between which the status of ship functions changes. The major phases include: (1) design, construction and commissioning; (2) entering port, berthing, unberthing and leaving port; (3) loading and unloading; (4) dry docking; and (5) decommissioning and disposal. A ship consists of a set of systems such as machinery, control system, electrical system, communication system, navigation system, piping and pumping system and pressure plant. A serious failure of a system may cause disastrous consequences. Risk assessment may be carried out with respect to each phase of shipping and each marine system. The likelihood of occurrence of each failure event and its possible consequences can be assessed using various safety assessment techniques such as an influence diagram which is a combination of fault tree analysis and event tree analysis. An influence diagram may be used to deal with the escalation of an accident and mitigation aspects such as the evaluation of people, containment of oil pollutants, etc. Generic data or expert judgements may be used in risk assessment.

3.3. Risk control options

This step aims at proposing effective and practical risk control options. High risk areas can be identified from the information produced in risk assessment and then the identification of risk control measures can be initiated. In general, risk control measures have a range of the following attributes:

1. those relating to the fundamental type of risk reduction (i.e. preventative or mitigating);
2. those relating to the type of action required and therefore to the costs of the action (i.e. engineering or procedural); and
3. those relating to the confidence that can be placed in the measure (i.e. active or passive, single or redundant).

Risk control measures can reduce frequency of failures and/or mitigate their possible efforts and consequences. Structural review techniques may be used to identify all possible risk control measures for cost-benefit decision making.

3.4. Cost-benefit assessment

This step aims at identifying benefits from reduced risks and costs associated with the implementation of each risk control option for comparisons. To conduct cost-benefit assessment, it is required to set a base case that can be used as a reference for comparisons. A base case is the baseline for analysis reflecting the existing situation and what actually happens rather than what is supposed to happen. A base case reflects the existing levels of risk associated with the shipping activity before the implementation of risk control. Option costs and option benefits can be estimated. The Cost of Unit Risk Reduction (CURR) for each risk control option can then be obtained by dividing the net present value of costs and benefits by the combined reduction in mortality and injury risks where 50 minor injuries are equivalent to 10 serious injuries or to 1 life. Those CURR values provide a relative ranking of the efficiency of alternative risk control options.

The evaluation of costs and benefits may be conducted using various methods and techniques. It should be initially carried out for the overall situation and then for those interested entities influenced by the problem consideration.

3.5. Decision making

This step aims at making decisions and giving recommendations for safety improvement. The information generated can be used to assist in the choice of cost-effective and equitable changes and to select the best risk control option.

4. Risk criteria for ship safety assessment

Risk criteria are standards which represent a view, usually that of a regulator, of how much risk is acceptable/tolerable (HSE, 1995). In the decision-making process, criteria may be used to determine if risks are acceptable, unacceptable or need to reduce to ALARP. When Quantitative Risk Assessment (QRA) is performed, it is required to use numerical risk criteria. The shipping industry has functioned reasonably well for a long time without consciously making use of risk criteria. Recently, QRA has been used extensively for ships carrying hazardous cargoes in port areas and for ships operating in the offshore industry (Spouse, 1997). It is noted that in general there is no quantitative criteria in formal safety assessment even for a particular type of ship although the MCA trial applications have used QRA to a certain extent. As time goes on, it is believed that more QRA will be conducted in marine safety assessment. Therefore, numerical risk criteria in the shipping industry need to be dealt with in more detail.

Risk assessment involves uncertainties. Therefore it may not be suitable to use risk criteria as inflexible rules. The application of numerical risk criteria may not always be appropriate because of uncertainties in inputs. Accordingly, acceptance is unlikely to be based solely on a numerical risk assessment. Risk criteria may be different for different individuals. They would also vary between societies and alter with time, accident experience and changing expectation of life. Risk criteria can therefore only assist judgements and be used as guidelines for decision making.

In different industries, risk criteria are also different. For example, in the aviation industry, failure with catastrophic effects must have a frequency less than 10^{-9} per aircraft flying hour. In the nuclear industry, the basic principles of the safety policy recommended by the International Commission Radiological Protection (ICRP) are that no practice shall be adopted unless it has a positive net benefit; that all exposures shall be kept As Low As Reasonably Achievable, taking economic and social factors into account; and that individual radiation doses shall not exceed specific criteria (ICRP, 1977). There are no explicit criteria used by ICRP.

As far as risk criteria for ships are concerned, the general criteria may include: (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; and (4) the risks of catastrophic accidents should be a small proportion of the total (Spouse, 1997). More specifically, individual risk criteria and social risk criteria need to be defined. For example, for maximum tolerable risk for workers may be 10^{-6} per year according to the HSE industrial risk criteria. In the regions between the maximum tolerable and broadly acceptable levels, risks should be reduced to ALARP, taking costs and benefits of any further risk reduction into account.

5. Possible application areas of formal safety assessment

The formal safety assessment philosophy has been approved by the IMO for reviewing the current safety and environmental protection regulations and studying any new element proposal by the IMO, and justifying and demonstrating a new element proposal to the IMO by an individual administration. Further applications may include: the use of formal safety assessment for granting exemptions or accepting equivalent solutions for specific ships under the provisions of SOLAS Chapter 1 by an individual administration; for demonstrating the safety of a specific ship and its operation in compliance with mandatory requirements to the acceptance of the Flag Administration by an individual owner; and as a management tool to facilitate the identification and control of risks as a part of the Safety Management System (SMS) in compliance with the IMS Code by an individual owner. Several possible options regarding the application of formal safety assessment are currently still under investigation at the IMO. Among the possible application options, the individual ship approach may have great impact on marine safety and change the nature of the safety regulations at sea since it may lead to deviation from traditional prescriptive requirements in the conventions towards performance-based criteria. This may be supported by ship-type specific information. However, this would raise concern due to the difficulty in the safety evaluation process by other administrations, particularly when acting as port states, although the merits of it may also be very significant. It is believed that, due to its technical complexity, it may take some time for formal safety assessment to be enforced at any possible areas described above. At the moment, unlike in the UK offshore industry, there is no intention to put in place a requirement for individual ship safety cases.

It is also very important to take into account human error problems in formal safety assessment. Factors such as language, education, training, etc., that affect human error, need to be taken into account. The application of formal safety assessment may also encourage the Flag States to collect operation data. Another important aspect that needs to be considered is the data problem. The confidence of formal safety assessment greatly depends on the reliability of failure data. If formal safety assessment is applied, it may facilitate the collection of useful data on operational experience which can be used for effective pre-active safety assessment.

6. Further development

Shipping is such a complex process with high uncertainty involved. A ship is a complex and expensive engineering structure composed of many systems and which is usually different from other types of ship (Wang and Ruxton, 1997). Ships need to constantly adopt new approaches, new technology, new hazardous cargoes, etc., and each element brings with it a new hazard in one form or another. Therefore, a very generic formal safety assessment framework should cover all possible areas including those where it is difficult to apply traditional safety assessment techniques. Lack of reliable safety data and lack of confidence in safety assessment have been two major problems in safety analysis of various engineering activities. This is particularly true in formal ship safety assessment due to the fact that level of uncertainty is high. To solve such problems, further development may be required in the following four areas:

1. review of the existing safety analysis techniques in the context of formal ship safety assessment;
2. novel ship safety assessment techniques;
3. advanced cost-benefit and techno-economic analysis; and
4. case studies.

Safety assessment techniques currently used in ship safety assessment need to be further studied and the criteria for effective use of them need to be established in safety assessment. It is not feasible to apply one safety assessment method to identify and assess risks in a complete ship's life cycle. An effective way is that different safety assessment methods are applied individually or in combination, depending on the particular situation, to assess risks with respect to each phase of the ship's life cycle and each accident category (Wang and Ruxton, 1997). Existing ship safety assessment methods need to be studied regarding safety data flow and their interrelations to make full use of the advantages of each method. The conditions in which particular safety assessment methods are most effectively applied also need to be studied in the context of the full ship life cycle and accident categories.

In ship safety assessment, in many cases, it may often be difficult to identify and assess hazards using traditional safety assessment techniques due to the lack of sufficient safety data. Therefore, novel safety assessment techniques for ship safety assessment may be required. A subjective safety assessment approach may be expected to deal with high uncertainties, particularly in situations where a ship with many new design/operation features or a ship operating in a very changeable environment is studied (Wang et al., 1996a). A subjective safety assessment method needs to be studied in depth in the context of formal safety assessment to allow safety-based design/operation decisions to be made.

Novel decision-making techniques based on safety assessment are also required to make design and operation decisions effectively and efficiently. When operational aspects are considered in the decision-making process, it may be difficult to compare costs and benefits for all systems on a common basis since costs and benefits of systems vary differently with operational aspects. Furthermore, when more design parameters such as reliability are taken into account in the decision-making process, simple comparison of costs and benefits cannot be conducted. It may be required to develop an effective techno-economic model which takes various costs and benefits into account (Wang et al., 1996b). Formal Multiple Criteria Decision-Making techniques may be applied to process the mathematical model to determine where risk reduction actions are cost-effective and how this is to be done (Yang and Sen, 1994; Wang et al., 1996b).

Software safety analysis is another area where further study is required. In recent years, advances in computer technology have been increasingly used to fulfil control tasks to reduce human error and to provide operators with a better working environment in ships. This has resulted in the development of more and more software-intensive systems. However, the utilisation of software in control system has introduced new failure modes and created problems in the development of safety-critical systems. The DCR have dealt with this issue in the UK offshore industry. In formal ship safety assessment, every safety-critical system also needs to be investigated to make sure that it is impossible or extremely unlikely that its behaviour will lead to a catastrophic failure of the system and also to provide evidence for both the developers and the assessment authorities that the risk associated with the software is acceptable within the overall system risks (Wang, 1997). In formal ship safety assessment, safety-critical systems may need to be studied together with system safety assessment to minimise risks.

More test case studies also need to be carried out to evaluate and modify the formal ship assessment framework and associated techniques and to provide more detailed guidelines for the employment of them. This would enable validation of them and can also direct the further development of suitable ship safety assessment techniques and facilitate technology transfer to industries.

7. Concluding remarks

It is clear that it would be possible to prevent marine accidents by good design, training, and operation in an appropriate systematic management system. As the public concern regarding maritime safety increases, more and more attention has been directed to the application of formal safety assessment of ships as a regulatory tool. It is believed that the adoption of such a tool in ship design and operation will reduce maritime risks to a minimum level. More scientific research is required in the area of formal ship safety assessment.

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