Perception and management of risk-dependence on people and systems

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SYNOPSIS

This paper explores the evidence from ship operation of the interaction between people and shipboard systems, the impact of changes in technology and the regulatory safeguards that are in place. The evidence from service is discussed against the perceptions of risk, identifying areas where changes in understanding and knowledge could produce benefits. The potential benefits to shipping in terms of reductions in losses that could result from changing attitudes within the industry and recognising the influence of perceptions of both risk and the extent of the complete marine engineering system are discussed. In particular the subject is considered in relation to an industry which depends on large design and build-to-order artefacts, operating in arduous and highly competitive environments. The paper emphasises the critical interdependence of people (in design, manufacture and operation) and engineered marine systems.

INTRODUCTION

With the almost complete demise of flight engineers on airliners and riding engineers on the railways, shipping remains the last major transport industry that operates with an ever-present, professional engineering staff which is capable of the management, maintenance and repair of a complex engineering artefact. Although this paper is not restricted, when discussing the impact of people on shipboard operations, to the engineering departments onboard merchant ships there is a strong emphasis on the interaction between people and engineering systems, primarily the electrical, electronic and mechanical systems. Although some information is cited from recent work carried out by the author and his colleagues in terms of reanalysing the copious information provided in the formal reports of the investigations of marine accidents a more detailed review can be found elsewhere.

It has become increasingly evident to the author that the achievement of safety at sea depends on the availability of both dependable systems and competent people and that the effective management of safety can only be achieved by considering these two aspects together. Dependability of the hardware, and the embedded computer software, infers not only availability and reliability but also a measure of functional correctness in the context of the application. Competence is intended to be a much wider skills attribute than that associated with the basic seafaring qualifications that is recognised in terms of Certificates of Competence. Advances in safety can be made by tackling either of the two facets independently but any major improvement can only be achieved by an integrated approach. Similar arguments can be assigned to all risks associated with marine operations and it is, therefore, logical that consideration of the totality of marine engineering systems, including people and their behaviours, is fundamental to effective ship management. The following sections develop the principles involved, which have an impact on risk management, and the paper concludes by indicating some directional changes which could bring real benefits to marine risk management.

Author’s biography

Vaughan Pomeroy is responsible for the management of the research and development programme and the global naval business development activities of Lloyd’s Register. He joined Lloyd’s Register in 1980, after working in the aircraft industry and with mechanical and electrical engineering consultants, initially to work on engineering research and specialist projects. He has held management positions within Lloyd’s Register since 1987 and was appointed Deputy Chief Engineer Surveyor in 1992. He took up his present role in 2000. He is a Chartered Engineer, Chairman of the Board of Trustees and Fellow of the Institute of Marine Engineering, Science and Technology, a Fellow of the Institution of Mechanical Engineers, a Fellow of the Royal Institution of Naval Architects and a graduate of the University of Cambridge.
PERCEPTION AND REALITY

Perception of risk has a major influence on human behaviour, despite the often considerable gap between that perception and the demonstrable factual evidence. The dominating influence of perception will always restrict the scope for constructing safety arguments based on scientific analysis. The perception of risk is clearly important and there is a need to understand whether there are differences between people in different operational and management roles and from different cultural backgrounds, given the international nature of shipping. Recognising this gap in knowledge, the Seafarers International Research Centre (SIRC) started an interesting investigation which is intended to provide some indications about how risk is perceived. After all, we know that in many cases the factual evidence is very different from the perception. As an example, much literature relating to the age of sail refers to the dangers of working aloft but recent research using the records of ships’ surgeons suggests that most deaths and injuries, other than due to disease or battle, were caused by trips and falls at deck level and not from heights. In fact, the new evidence looks rather similar to an analysis of the causes of personal injuries on a modern ship.

Fig 1 Loss rates for the world fleet 1980 - 2004
To give another example, shipping is often perceived to be a dangerous activity and the impression given from some quarters is that nothing is improving (for example see Langewiesche⁴). Yet the factual evidence is entirely contrary, as shown in Fig 1, which presents the actual and constructive total losses for the last quarter century. Also indicated is the average age of the fleet, which shows a considerable increase, and so, against one variable which is often perceived as a primary factor when looking at any one incident, the real improvement looks quite remarkable. The two graphs are interesting because they show the influence of market conditions on the declaration of a constructive total loss. And yet it is clear that, despite the positive evidence, there are calls for further improvements to maritime safety and it must also be apparent that these gains are unlikely to be achieved through incremental enhancements to the current safety standards. Other evidence, however, is less encouraging. Underwriters continue to report large claims for losses other than total losses, particularly citing machinery damages. The quantum of loss associated with apparently minor damage is often very high as a result of consequential losses due to the time spent under repair or waiting for replacement parts.

There are arguments which suggest that in high-risk industries some degree of damage or loss is inevitable, as conceived in the thesis of Perrow⁵ in his concept of “normal accidents”. Although the marine industry is not often considered to be in the complex hi-tech league of aviation or nuclear power Perrow describes shipping as a “still more complex system” with characteristics of both risk taking and risk aversion. He also considers marine transport to be “an error inducing system, where perverse interconnections defeat safety goals as well as operating efficiencies.” The technology fix is usually to present more detailed or additional information to the operator without recognising the potential inadequacies in the human-technical system.

There are clear differences between perceptions and the records of incidents, if that evidence is assumed to reflect a measure of reality. In practice the regulators - and shipping is a heavily and internationally regulated activity - react more to perceptions. This is in spite of the decision within the International Maritime Organisation (IMO) to adopt the system of Formal Safety Assessment for rule-making, which itself uses a cost-benefit approach when making decisions. Taken to extreme there are many cases where regulators react to incidents by placing very stringent requirements on industry where the costs are clearly disproportionate to any possible benefits⁶. Perceptions, therefore, must also be related to considerations of value.

The illustration in Fig 2 shows the interactions between the willingness to take risks and the perception of risks, which is largely influenced by either personal experience or by awareness of a wider industry history, which itself is often clouded by the way the information has been acquired. The willingness to take risks is affected by a number of factors, including external pressures, real or imagined, to maintain a level of performance. The individual tries to balance the pressures, based on a personal assessment at the time of the decision. If the perception is that there is a low risk associated with a given action then clearly the willingness to take the risk is much greater, even if the perception is demonstrably incorrect.

![Fig 2 The balancing mechanism for risk](image-url)
The conclusion is that decision making on the management of risk must be focused on perceptions, balanced where possible by evidence of actual performance, particularly when considering the safety of people and the environment. Of course, evidence from operations can be used to modify perceptions but the recipients have to be willing to consider this information and conduct the necessary analysis.

For marine engineering systems, there is also a more prosaic consideration related directly to the business risks, which are in turn predominantly concerned with availability and reliability of equipment and systems. However, this apparently more straightforward situation may be misleading. Perceptions also drive decision-making where, for instance, the estimated cost and time to repair often is significantly different from reality or where assumptions about compatibility of equipment are based on superficial assessment and hopeful expectation rather than sound demonstration.

PEOPLE AND INCIDENTS

Study of the reports of investigations of marine incidents, and indeed other incidents involving transport systems, suggests that the conclusions focus on the most proximate cause. This has probably resulted in the human factors focus on the operator of the asset and, in particular, on their direct actions immediately prior to the incident. However, by looking at the underlying causal events the involvement of people naturally expands and, in this paper, consideration is given to the operators, maintainers, designers, constructors, installers, commissioners, regulators and users (such as passengers) - all of whom feature in the overall system.

It is well understood that in many industries there is an apparent unwillingness on the part of accident investigators to assign culpability to people except where it is clear that the proximate cause was some deliberate action by an identifiable person. It is, perhaps, easier or more acceptable to assign responsibility to some item of equipment or to “management systems” and this is common to a number of industries. The outcome is that a number of incidents are described as being the result of heavy weather, machinery failure or structural damage where a deeper analysis might identify a contribution to the incident which should correctly be assigned to the behaviour of people. Without necessarily assigning culpability, the omission of the human factor from the conclusions of the investigation can reduce the opportunities for improving safety when considering the learning outcomes from an incident. The underlying assumption should be that most failures are the result of a multitude of factors occurring in such a manner as to cause the incident and that many of the less proximate contributions relate to human action, or inaction. Only by attacking the underlying causes can real improvements be made.

By way of illustration the following would often be classified as machinery damages but clearly there are underlying failings in design, manufacture, installation, maintenance or operation:

- failure of a davit due to fatigue following an extremely high number of operating cycles (design error)
- a connecting rod which developed a fatigue crack and eventually fractured with the fatigue crack associated with a weld repair in the casting which was not heat treated (manufacturing error)
- a flexible coupling which became detached following failure of a tapered shaft due to fatigue caused by fretting as a result of an inadequate interference fit (installation error)
- detachment of a connecting rod from the lower bearing housing due to bolts being insufficiently tightened after dismantling (maintenance error)
- damage due to operation in ice (operational error)

If we are to introduce requirements that help to reduce the frequency and consequences of incidents and we know that human factors dominate the underlying causes we have to understand why people are predisposed to make these errors and what could be done to reduce the impact. This will include factors that will ensure that the engineering systems are more usable and, perhaps, more tolerant.

TRENDS IN MARINE ENGINEERING SYSTEMS

There has been a notable trend over recent years towards increasingly complex shipboard systems. Modern vessels now rely on a high degree of automation and supervisory control that adds considerably to the complexity of the total installation. The major driver for change has been to achieve
greater competitiveness through the potential for reduction in through-life costs. The advance in automation technology and increased use of programmable electronic systems in place of traditional hard-wired or pneumatic controls provides an opportunity to reduce both the first cost and operational costs.

The options available to the systems designer have expanded as the capability of electronic systems has increased remarkably. This explosion in potential has been quite extraordinary and is evident in terms of a very definite increase in the number of possible solutions. Furthermore, things can now be done that would have been impossible without this technology, such as build an engine that does not require a camshaft or enhance overall fuel efficiency on a continuous basis through a sophisticated power management system. The possibility of increasing the level of functionality encourages the design and construction of more complex systems that offer to the purchaser more options when using the ship. Moreover, with the progressive reduction in the cost of programmable devices, this increase in capability can be achieved cost effectively. The downside of this trend is that the owner is left with a system that may possess unnecessary, or in extreme cases even unknown, properties, and the result may well be beyond the understanding of the average, well-trained seafarer. The situation is made more complex by the interconnection of systems so that the possible interactions and dependencies are no longer as obvious as with older simple systems. In reality the system is usually not considered in its full context, which as shown in Fig 3 is a collection of individual components configured into higher-level systems, operated by people in the marine environment. To consider any one element in isolation is likely to provide an incomplete picture.

It is a well-established practice that marine systems are designed to tolerate a single failure without presenting a major hazard. As systems become more complex and integrated it is difficult to demonstrate tolerance of a “single failure” and this becomes even more problematic when the systems feature dynamic levels of integration and reversionary modes of operation. The complex integrated system can result in multiple failures and this outcome has to be taken into account. However, in many cases it is possible to configure systems so that failure by the user is reasonably unlikely and can be tolerated in the same way as a mechanical failure - it should not lead immediately to a hazardous condition. Essentially, the designer is providing the user with a system that can be used in a manner that will allow the user more time to react in the event of a failure and, therefore, improve the probability of corrective action being taken. This requires the designer to look at wider definitions of systems rather than the traditional breakdown used in marine engineering. In practice, little consideration is given in this regard and seafarers simply make use of what is provided.

It may seem obvious that systems must be usable by sea-going staff of average competence - but this demands more than the systematic conformance of the working environment to ergonomic principles. Unfortunately, there are plentiful examples of modern ships where the background noise, vibration and
lighting levels do not provide an ideal working environment for the crew. It is also possible for the basic ergonomic requirements of the installation to be addressed but for the system to become unusable under certain circumstances, notably during abnormal operations and emergencies. The design of bridges and control rooms should reflect the operating procedures, both routine and emergency, and suit the characteristics, capabilities, experience and training of the crew. As it is, errors can often be traced to a misunderstanding of the information supplied by the machine interface or to an overload of information or unachievable expectations of crew performance. In short, a badly designed interface or ill-considered allocation of function encourages mistakes that no amount of training or management intervention can completely mitigate. The introduction of new technologies brings both opportunity and threats associated with the changes and some recent research by Bailey raises some questions about how effective the processes of introduction are in practice. The study of the effectiveness of the introduction of an entirely new technological capability in AIS, which is implemented as a result of international regulation, provides an interesting assessment of a genuine step change.

Ideally, design should include active participation by the people who will actually operate the system (user-centred design) but different crews will inevitably operate the ship during its service lifetime. Nevertheless, user input is extremely valuable and should be sought at appropriate times. It should also influence any standards, codes of practice and rules that are referenced by the designer. It is, of course, much more straightforward to write a standard for a single discrete item, defining dimensions, characteristics, materials and interfaces. “Systems engineering methods” provide an approach that permits the designer to select the best solution whilst ensuring that the key requirements are satisfied within a given context. There is actually very little evidence to suggest that a systems engineering approach is being adopted when designing shipboard applications, which presents a significant risk to the seafarer and the operating companies. However, the more open approach to definition of requirements and explicit trade-offs between design parameters can make it easier to incorporate the human element aspects since it inevitably means taking a non-prescriptive goal-setting approach.

Improvements in the reliability of equipment and extended intervals between routine overhaul have resulted in a significant change in the demand for ships’ staff. The decrease in maintenance and repair work is consistent with the reduction in crew numbers but it also significantly reduces the exposure of sea-going engineers to the learning experience that is associated with these tasks. In effect, the lack of opportunity to learn from “precursor” events may reduce effectiveness when dealing with a hazard. The environment that provided the experience for dealing competently with all manner of abnormal situations has been changed by the advances in technology that have increased reliability and reduced maintenance. Familiarity with items of equipment has been reduced by the reduction in routine intervention.

Despite the warnings of the potential for software errors leading to major disasters, there is very little evidence of these being considered in a rational manner. The scale of application of software-based systems and the scope of their application became very evident during the “Millennium Bug period”, which made ship operators aware of how many programmable devices were actually present on a modern ship. Although no significant failures were reported, the associated investigation programmes did result in operators questioning the need for many of the less essential software-based systems and using the opportunity to rationalise the inventory. Software system failures generally arise from poor specification, inadequate consideration of the intended use of a system or poor development and testing procedures. The increase in the dependence on software solutions since the beginning of the current century means that the advice that was given to revert to manual operation through potentially critical date/time combinations around the Millennium change would no longer be realistic. This change is irreversible and rapid.

At the same time, the operator is faced with an increased dependence on marine electronics, assuming that the systems do exactly what the operator expects. The electronic systems for automatic control (even of complicated operational patterns some of which would simply not be possible to achieve using traditional manual controls) and safety monitoring systems that provide shut downs and alarms are all inherently highly reliable. Given the reliability of machinery and the commonly held, but questionable, presumption that associated alarm and control systems are, essentially, fault-free, it is not unreasonable that the human operator is comfortable relying on the systems. To some degree, the roles of the automation and safety systems and the human operator have been reversed. The operation is now controlled automatically with human supervision rather than the control and alarm system assisting the human operator to identify malfunctions at an early stage. The reliance on the system, with the human
relegated to monitoring the progress of the ship, can encourage a suspension of the traditional seafaring skills of the crew. Dulling of the response to visual signals, such as observing weather changes from the bridge, or to smells and sounds in an engine room because the user is focused on monitoring information presented to him, represents a danger to safety that is often overlooked.

Certainly the improved functionality of support systems, including navigation, communication, control of main and auxiliary machinery and general monitoring and alarm, has been essential in the reduction of crew numbers. This reduction in numbers of available people has more complex consequences, including crew fatigue. Some maintenance tasks, such as repairing machinery after failure, simply cannot be handled by the number of people available, thereby presenting an additional potential hazard to the ship. In designing the total ship system it is, therefore, imperative that the corresponding workloads are considered, including the availability of people to deal with a series of reasonably foreseeable incidents, under all operational workloads and sea conditions. The ISM Code requires that mitigation measures be put in place for all identified hazards. It has to be recognised that identification of all hazards is a challenge with software based systems. The risk register that forms part of the Dependable Systems Review, developed by Lloyd’s Register, offers a potential solution.

As the level of complexity increases so the human element becomes more deeply embedded amongst the physical elements. As machinery and equipment are left to operate unattended, the monitoring systems detect warning signals and prod the control systems to take immediate action. The crew member that eventually gets called in to deal with any resulting major problem enters a situation part through. Without time to ‘gear up’, it is all too easy to misjudge the situation in the confusion and to initiate actions that exacerbate the situation. Arguably, the seagoing engineers are no longer expected to possess high calibre diagnostic skills, since they can rely on the automation, but they do need to be able to assimilate information provided by the systems. The skills taught at training colleges may not be sufficient to reflect the changes in the industry.

**RISK CONTROL HIERARCHY**

Reducing risk can be achieved either by reducing the frequency of occurrence of the initiating hazard or by reducing the consequence that could result from a particular set of hazard conditions, or a combination of both. The methods available are well developed and proven. When considering the effectiveness of differing approaches to minimising risk through the application of risk-control measures it is necessary to understand that different solutions might produce very different outcomes. Shown diagrammatically in Fig 4 there is a clear hierarchy and the designer and operator should select the most effective solution, but this clearly demands an understanding by the designer of how the ship will be operated and an understanding by the operator of what the designer intended.

![Hierarchy of risk-control measures in terms of effectiveness](Fig 4)
The optimum solution will be to eliminate the hazard entirely and, where possible, this strategy should be followed. In many cases this is simply not possible, so it is accepted that marine operations involve some inherent risks. Effort is usually focused on reducing the risk by making design or operational changes. There is comment above relating to the increased complexity that can be introduced through adding functionality to alarm arrangements, and there is evidence that the response to alarms is sometimes inadequate. Even where engineering solutions are put in place these are not always fully effective in practice. There is a trend towards engineering out the operator as the system becomes more complex because the designer believes that the operators are no longer capable of understanding the system operation and interference could result in damage to the equipment.

However, there are many cases where the final solution adopted falls into one of the least effective categories through reliance on procedures or warning notices, or on personal behaviour and self protection. The challenge at this end of the scale is that risk control, in effect, falls to the individual who may elect, for whatever reason, to take actions which do not conform to the established and prescribed safe practice. It is still common to rely on notices at engine control stations which advise of a barred speed range, on account of predicted critical vibration conditions in the shafting system. This warning does not preclude operation within the barred speed range although such operation could, and has been found to, cause catastrophic failure resulting in loss of propulsion and, in extreme cases, flooding. An automatic arrangement can be included in the control system, which would protect against operation in the barred speed range, but this could be too restrictive under abnormal operating conditions. The options available all have advantages and disadvantages, so there is no obvious "right solution". It is a system problem with physical limitations and a necessary input from people - the operators.

It is also a matter of record that seafarers continue to suffer a relatively high risk of personal injury and even death during routine operations. Despite operational procedures for potentially hazardous tasks, such as entry into confined spaces and tanks, people still take risks and suffer the consequences. Reliance is placed on the procedures and training but the evidence suggests that apparently competent people fail to follow safe working practices. However, it is difficult to see how all of the potentially hazardous operating requirements can be “engineered out” and the improvement of personal safety must depend on improved awareness training and effective enforcement of safe working practices. It is also necessary to ensure that, in defining the operating practices and the controls, full account is taken of cultural issues. There are many examples in modern regulatory thinking that are formulated on western practices, often developed in other industries, and an assumption that these can simply be successfully translated into the multi-cultural maritime environment.

REGULATION AND MANAGEMENT OF RISKS

The marine industry relies on regulation and demonstration of compliance and it is incumbent on those who are responsible for developing and publishing the standards which are used to ensure that these are relevant, appropriate and sufficient. It is clear that developments in technology are occurring at a fast rate and that this change has outstripped the development of the essential standards. Furthermore, in the future, to address the message of the previous sections of this paper, standards should be written on the basis of a complex human-technical system, in non-prescriptive terms so that the aim is clear and relatively independent of the technical solution wherever possible.

To be effective, good standards will be based on some key principles, which are similar to the requirements for good legislation:

- don’t make rules unless the smallest company will be able to cope
- don’t make rules unless the benefits justify the imposed costs
- don’t make detailed prescriptive rules when a goal can be defined and industry can decide how to achieve it

Of course, there are a number of practical challenges, not least associated with the development of a common vocabulary and understanding of risk issues and the interactions within systems. It has to be understood that unforeseen things happen, but most are, in fact, foreseeable with imagination. The standards need to be clear and verifiable and, wherever possible, the user should be able to understand which hazards are being addressed by any specific requirement. There should also be a deliberate effort made to reduce the reliance on the less effective risk control options.
The marine industry is regarded as high risk and the way that the risks are communicated to governments and others has to recognise the generally accepted approaches. Whilst compliance with regulations, rules and standards may demonstrate that reasonable measures have been taken to mitigate identified risks, somehow public confidence has to be established or re-established. This involves the complete system and modern society demands more than statements along the lines of “Trust me – I am a professional and I know what I am doing”. The industry has to be prepared to demonstrate an understanding of the risks and to discuss how these are being managed, and that is not possible without a clear understanding of the behaviour of people and engineering systems, in concert.

CONCLUDING REMARKS

The paper set out to argue the case for considering management of marine risks in a genuinely holistic manner. This represents a challenge to the industry and requires some changes in the way that engineering systems are designed, configured, maintained and operated to take greater account of the behaviour of people.

The awareness campaign being delivered to marine professionals under the management of the Nautical Institute with financial support from Lloyd’s Register through the Alert! Quarterly bulletin, and the number of conferences and training opportunities, all suggest that the marine industry is receptive to efforts to improve safety through better management of the human element. The conclusions drawn by Wagemaar and Groeneweg11 in 1987 are still very relevant when they state, “The analysis of 100 accidents at sea has brought us to the conclusion that the acts which lead to an accident are part of a complex causal network that cannot be overseen by the actors. Errors do not look like errors at the time they are perpetrated, and the accidents that are caused by them look impossible beforehand. However, telling people to change their behaviour when facing accidents will not help, because they rarely believe they are facing accidents.” This exemplifies the points raised by Perrow, in that marine transport fosters unconscious risk aversion and risk taking.

Regulation and training have to recognise the complex interactions between engineering systems and people, demanding dependability and competence and mutual compatibility. Shipping may have become safer but further improvements will be necessary if the expectations of society are to be met. To make these gains the industry has to determine whether incremental changes will be effective and where a change of approach is essential. Safe operation of ships with increasingly complex systems will make demands on people and will require dependable systems and competent people. Incident analysis shows that human behaviour underlies many of the marine accidents and there is an over-reliance on last-line-of-defence risk-control measures. Fundamentally the industry has to change to become one that is not an “error-inducing system”. In making these changes we certainly have to understand perceptions of risk as it is these perceptions that will drive the behavioural changes that are necessary.

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