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Improving Human Factors in Marine Maintenance

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Abstract

The significance of human factors in marine operations has been increasingly recognized over the last decade. However, limited attention has, until recently, been given to the important issue of human factors in the quality of marine structures and, in particular, their maintenance.

This paper presents an approach to the assessment of shipboard maintenance operations using human factors techniques to improve efficiency and safety. The approach is based upon similar work that has been undertaken in the nuclear, offshore and aviation industries and includes one of the authors' own direct experience of human factors assessment of maintenance.

The assessment approach proposed in this paper is aimed at addressing key human factors issues in the performance of shipboard maintenance. These include, in particular, the quality of working procedures; training; workload and task design; design for maintainability; the workplace and working environment; and the safety culture within the ship owner/manager's organization.

The paper reports on the use of the assessment approach and the benefits which were gained from a study conducted in the civil aviation industry and discusses the potential benefits which similar studies would bring to ship owners, managers and operators.

1. Introduction

Maintenance errors have been highlighted as significant contributory factors in a number of major accidents, across a range of industries. In the UK, examples of major accidents or incidents to which maintenance has contributed include the fire and explosion on the Piper Alpha offshore production facility, Cullen [1], signaling failures leading to the Clapham Junction railway crash, Hidden [2], and the incorrect fitting of a windscreen on a BAC One-Eleven aircraft, leading to subsequent failure of the windscreen on take-off, AAIB, [3].

Most industries recognize that the cost of maintenance errors can lead to highly expensive or, in some cases, catastrophic, system failure, Bond [4]. Given the central role that the human (i.e. maintenance engineer) plays in maintenance activities there has been a considerable amount of Human Factors (HF) work undertaken in the field of maintenance, Bond [4], Oborne [5], Megaw, [6], Morris and Rouse [7], and Shepherd [8], covering a range of industries. This work has drawn from a number of HF related disciplines. These have included ergonomics, cognitive psychology and more recently, with the advent of computer-based support tools for fault-finding and maintenance planning, knowledge engineering.

HF studies and assessments, in particular in human reliability and human error identification and analysis, have led to an increasing acknowledgment that reducing the potential for human error depends as much upon the management and organizational environment in which the work activity is situated as it does upon the human directly responsible for carrying out a task, Shepherd[8], Seminara [9].

HF analyses of maintenance provide an insight into the nature and context of maintenance tasks and the elements that influence human performance in carrying out such tasks. Based upon this insight, it is possible to identify important considerations in the provision of support to the maintenance engineer. Recommendations can be made in the following areas:

- job and task design,
- training,
- the working environment,

- provision of appropriate automated task support,
- organizational structure,
- the development or enhancement of safety culture.

Maintenance is recognized as an important activity in the maritime environment where inadequacies in the way that it is carried out can have significant safety and business implications. The UK P& I club statistics show the proportion of mechanical, equipment and structural failures to be as high as 23%, with a lack of proper maintenance being a major contributor to these failures. A search within Lloyd's Register's own casualty database of vessels between 100 and 400 meters, examining casualties over the last five years, revealed that a significant number of the reports filed made reference to crew negligence, poor repair, poor workmanship, or poor welding as causes of repairs being reported. One example referred to a case where an unattended grit blasting machine 'blew a hole' in the bottom shell. Other examples included incorrect operation of lifting gear and overloading of tanktops and hatch covers.

With increasing awareness of the central role of human performance and human reliability in ship operation and maintenance, a concerted response has come from the international shipping community with the adoption of the ISM Code, IMO [10]. Chapter 10 of this code requires that maintenance of safety critical equipment is planned and covered by management system procedures.

The seagoing ship is an immensely complicated engineering system operating in a harsh environment. This leads to maintenance representing a large cost item in keeping a vessel at sea. It has been estimated that typical annual technical costs of various ships approaches an average level of 25% of the total operating costs (i.e. crew, technical, management and others), and of those costs it was identified ship maintenance represents up to 60% of the ship's operating costs, Tzannatos and Markakis [11].

The proportionally high cost of maintenance leads to it being one of the first areas to suffer when commercial pressures increase. An example of such a situation was in evidence during the 1970's and early 80's in the marine industry when freight rates dropped. The reduction in ship manning brought about by the increased use of automation and the reduction in port stay has also affected the amount of maintenance being carried out. The need to critically examine the maintenance procedures and practices becomes more important as the time and resources available are reduced.

The significance of the deterioration of the vessel and its equipment has long been recognized by the regulatory bodies. These have specified which equipment is considered to be fundamental to the safe operation of the vessel and defined timescales for inspection. These traditional inspection and survey methods require the equipment to be disassembled and then reassembled. Human error can arise at both the disassembly and more frequently at the subsequent reassembly. Errors in the latter often lie undetected until later. An example of this is in the failures of lifeboat launching equipment following the introduction of the on-load/off-load release gear. Various causes for these failures are cited as contributory, with mis-operation and inadequate maintenance often being involved, Speight [23].

Inadequate maintenance and errors in ship operation also have an impact upon the structure of a vessel. Investigation into Bulk Carrier safety, LR [24], has lead to the identification of a number of factors that are being addressed within the shipping industry. One factor identified has been the inadequacy of maintenance schedules in addressing damage to the ship's side shell structure resulting from discharge of cargo.

Engine room maintenance provides an example where a lack of consideration of human factors has both immediate and long term implications for safety. A study by NKK [25] identified that a significant number of engine room fires occurred during repairs at the shipyard and that the main cause of these fires was gas cutting or welding during repairs. The study report highlights the fact that engine rooms during maintenance have a poor working environment, such as poor scaffolding, and overhauling equipment, and with flammable oils spilled on the floor. Furthermore, such maintenance operations commonly involve a large number of crew members and other maintenance working parties working in a relatively confined space. These 'mixed' working groups also introduce potential problems of communications and supervisory control of maintenance tasks which can lead to the introduction of human errors. The specific example of engine room fires highlighted by the NKK study obviously has immediate health and safety implications (i.e. fires leading from welding work) but also have longer term implications where latent structural and mechanical defects can be introduced during repair work due to the poor working environment and an overall lack of consideration of human factors.

This paper now reports upon the approach taken to an HF assessment study of current maintenance practice in the civil aviation industry, CAA [22] and goes on to consider the potential benefits that similar studies would present to the marine industry.

2. The Scope of Human Factors

For the purposes of this paper, HF, as a discipline, is defined as the study of those aspects of the design, management and organization of a human's tasks which influence human performance, and therefore, influence the potential for error in carrying out the tasks. This paper is concerned primarily with maintenance tasks.

2.1 Human Factors Issues

HF encompasses a broad range of issues. In terms of a HF assessment of maintenance it is possible to identify a subset of key HF issues categorized in the following way:

Safety Culture

Issues to be considered include:

(a) awareness of the company safety policy and management commitment to safety,

(b) control of quality in maintenance,

(c) systems for raising safety concerns,

(d) systems for reporting accidents/near misses and learning lessons from them,

(e) "blame-free" culture for genuine errors.

Procedures

Issues to be considered include:

(a) requirements for use of procedures,

(b) content, format, usability and ease of selection of procedures,

(c) design of procedures for the intended end-user,

(d) clear indication of need to follow procedures,

(e) administrative control of procedure change.

Workplace and Working Environment

Issues to be considered include:

(a) posture in carrying out tasks,

(b) internal and external environmental conditions, including temperature, humidity, vibration, noise, lighting, weather, and motion,

(c) technical support facilities,

(d) administrative and personnel support facilities.

Task Design and Job Organization

Issues to be considered include:

(a) potential for conflicts influencing decision making (e.g. between safety and commercial requirements),

(b) workload (both high and low),

(c) allocation of responsibilities,

(d) effect of job content on motivation and attitude,

(e) adequacy of supervision.

Training

Issues to be considered include:

(a) scope of coverage of training courses (to address all the skills and knowledge required for the job including information retrieval),

(b) refresher training requirements,

(c) identification of individual training needs.

Design for Maintenance

Issues to be considered include:

(a) location of items to be maintained and ease of access,

(b) potential for incorrect/inadequate spares to be installed,

(c) systems of identifying out-of-service components,

(d) need for and availability of special tools and equipment.

Note that many of these issues, particularly those categorized under Safety Culture, are generic HF issues which are equally applicable to normal and emergency operation as well as to maintenance. To assess these issues in the context of maintenance requires an understanding of their specific applicability to maintenance and related activities (e.g. maintenance planning, design modifications, etc.).

2.2 Human Factors Methods

HF provides a wide range of methods and techniques with which to assess and analyze issues such as those identified in the previous section. Two particular categories of HF methods; namely, Task Analysis, and Human Error Identification methods are discussed here.

Task Analysis Methods

Task Analysis is a global term referring to a set of techniques used to describe and assess particular attributes of human tasks. Kirwan and Ainsworth [12] defines task analysis as "the study of what an operator (or team of operators) is required to do, in terms of actions and/or cognitive processes, to achieve a system goal."

Task Analysis can be used for a variety of reasons and to address a variety of concerns. It can contribute to safety by identifying hazards, defining safe systems of work, assisting in good design for human operation, forming the basis for an assessment of human error or helping accident investigation. Similarly it can be used to enhance productivity, efficiency and availability by supporting design decisions concerning levels and types of automation, determining staffing requirements and optimizing job design arrangements.

Human Error Identification Methods

Human error identification is often carried out as a precursor to a formal quantitative human reliability assessment as part of a safety case or risk assessment. However, it can be, and often is, also used qualitatively, as a stand-alone tool, in order to assess a particular operation, identify potential errors and recommend remedial measures, or as an aid to accident investigation where the accident involves human error.

A variety of human error identification methods are available, almost exclusively based on different classifications, or 'taxonomies' of human error. It is not appropriate here to describe all of the human error taxonomies that have been developed and are reported in the HF literature. For more information on these classifications the reader is referred to Rasmussen [13], Reason [14] and [15].

2.3 A HF Study of Maintenance in the Civil Aviation Industry

An example of where the HF issues discussed above were addressed through the application of appropriate Task Analysis and Human Error Identification methods was in relation to a research study carried out by LR for the UK's Civil Aviation Authority (CAA). The background to this study was the recognition of the impact of HF shortcomings in maintenance activities which had been seen as contributing to recent aviation incidents such as, AAIB [3], AAIB [20], NTSB [21]. In addition, the benefits of attention to HF issues both in the ergonomics of cockpit design and in the management of crew resources had been recognized previously. The main objectives of the study were therefore:

- to identify good and bad examples of HF practices and determine the extent to which current approaches to HF issues might benefit from change,
- to determine how the application of HF methods and techniques can result in a safety benefit.

The approach to this study involved the following main stages:

- meetings, semi-structured interviews, and discussions with relevant Maintenance Managers and senior staff to discuss the scope and objectives of the study, familiarize the study team with the organization's maintenance activities and approach, and provide the framework and context for subsequent analysis,
- review of relevant maintenance documentation (in particular, related safety and quality manuals and maintenance procedures and practices),
- design and use of a confidential questionnaire to gain feedback on human factors issues from a representative sample of maintenance personnel. This questionnaire addressed the range of HF issues identified above, as far as possible in the context of the specific activities which the maintenance personnel carried out or were involved with. The questionnaire was based on both generic HF guidance, HFRG [17], HSE [18], IAEA[19], and a previous assessment of maintenance activities, Seminara [9], but was tailored to meet the specific needs of the aviation industry and the scope of the maintenance activities assessed,
- observations and discussions with maintenance personnel undertaking maintenance tasks. These encompassed both routine and non-routine activities in a range of scenarios and conditions, including different shifts and at different times within the shift pattern,
- Task Analysis of selected maintenance tasks, in the overall context of maintenance activities, making use of a Hierarchical Task Analysis (HTA) approach, Kirwan and Ainsworth [12]. Task analysis was used, primarily, as a means of gathering information and describing and assessing the way maintenance tasks are carried out in the context of the HF issues identified above. The use of task analysis also contributed to an understanding of maintenance tasks, which facilitated the use of the human error identification method (see below).

- Human Error Identification and analysis for selected maintenance tasks, using a formal human error identification methodology. The human error identification approach was based on a classification developed by Rouse and Rouse [16], see Tables 1 and 2. Their approach was seen as being particularly useful in that it allowed errors to be identified in terms of 'external error modes' (i.e. in terms of the way that errors are revealed) and these error modes encompassed all stages of a 'generic task' from monitoring, through formulating and testing an hypothesis, to identifying the goal to be achieved and executing the appropriate sequence of actions.

2.4 Potential Benefits of HF Studies of Maintenance

A study such as the one described above, can lead to a number of benefits in terms of safety, by reducing the potential for error, and often also in terms of efficiency and productivity, by improving human performance in maintenance. Such a study can highlight both good and bad examples of HF practices, raise the profile of the attention given to HF issues and, in so doing, improve the safety culture of the organization. Shortcomings in safety management practices, the design of procedures, the maintainability of components, the organization of work and design of maintenance tasks, the workplace and working environment and the training and re-training of maintenance personnel can be identified and improvements recommended.

Typical generic benefits include, for example:

- reduction in failures to follow rules, procedures and regulations in maintenance practices,
- improved attitude and commitment to good safety management practices,
- enhanced coverage, accessibility and usability of maintenance procedures and other maintenance-related information,
- identification of design shortcomings in terms of component maintainability (e.g. location, access, workspace), and consequently their elimination, or at least the minimization of their impact,
- provision of job aids, improved time planning, more independent supervision and optimized workload,
- improved reliability and availability of technical information, tools, test equipment and spare parts,
- improved analysis of individual training needs (e.g. technical, inter-personal, software-related), verification of training adequacy and management of change to the training courses (e.g. following design changes, incidents or feedback from trainees),
- better shift handover procedures and practices and enhanced communication, in general,
- enhanced reporting of the HF contribution to incidents and near misses, to ensure continued feedback of HF issues and concerns and to enable continuous improvement.

2.5 Implications for the Marine Industry

It is suggested that studies of the type described above are as relevant in the marine sector as they are in the civil aviation sector, or indeed, other industrial sectors which might benefit from improvements to safety, reliability, and productivity in maintenance activities. A number of potential benefits to the marine industry are discussed below.

i) The issue of multi-cultural crews is gaining in importance. The nationality of ship's officers and crews is becoming more mixed with, on some ships, as many as four or five different nationalities on board at any one time. A quality maintenance regime is reliant upon good (verbal and written) communication. Communication (and information transfer) is a key element of carrying out the range of maintenance tasks such as inspection, diagnosis, calibration, modification, and refitting. Issues associated with cultural differences in the reaction to command structures and authority onboard ship need to be considered alongside more obvious issues associated with the potential for human error resulting from language differences. The role that computer-based 'electronic manuals' can play in improving the transfer of information should also be assessed. All such issues need to be considered when establishing, conducting and monitoring a safe and efficient maintenance regime.

ii) A formalized HF assessment of maintenance tasks and human-centered design of procedures has a number of potential benefits. In particular, such an assessment enables a clear definition of roles and responsibilities and the information needs of those carrying out maintenance. With the trend towards a reduction in maintenance by ship's staff and a corresponding increase in the use of riding crews and shore side repair gangs there is a need for a clear definition of maintenance roles and responsibilities. HF methods provides a means for analyzing tasks and enable the clear definition of roles and allocation of responsibilities.

iii) The increasing use of automation and the introduction of unmanned machinery control systems and remote tank gauging systems places new requirements on the maintenance regime. Such systems include a vast array of sensors and software based components, requiring different range of information and knowledge on the part of the onboard engineers. A HF assessment will identify the impact of increased levels of automation on the tasks of the engineer during operation and maintenance, and will identify information and training requirements.

3. Conclusions

This paper has outlined a number of Human Factors issues relevant to maintenance activities and set down an approach to such issues by the use of Human Factors methods such as Task Analysis and Human Error. The approach has been applied successfully within the civil aviation sector, and it is suggested that, suitably tailored, it will provide similar benefits to the marine industry. There is a significant safety and business cost associated with inadequate maintenance, and as has been demonstrated in other industries, the application of Human Factors can lead to considerable improvements in human performance thereby improving the safety of personnel onboard and reducing business costs.

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Table 1 Rouse and Rouse Human Error Classification Scheme [16]

Error Classification	Error Mode	Brief Definition
Observation of System State	Excessive	Improper rechecking of correct readings of appropriate state variables
	Misinterpreted	Erroneous interpretation of correct readings of appropriate state variables
	Incorrect	Incorrect readings of appropriate state variables
	Incomplete	Failure to observe sufficient number of appropriate state variables
	Inappropriate	Observation of inappropriate state variables
	Lack	Failure to observe any state variables
Choice of Hypothesis	Inconsistent	Could not cause particular values of state variables observed
	Unlikely	Could cause values observed but much more likely causes should be considered first
	Costly	Could cause values observed but very costly (in time or money) place to start
	Irrelevant	Does not functionally relate to state variables observed
Testing of Hypothesis	Incomplete	Stopped before reaching a conclusion
	Acceptance	Reached wrong conclusion
	Rejection	Considered and discarded correct conclusion
	Lack	Hypothesis not tested
Choice of Goal	Incomplete	Insufficient specification of goal
	Incorrect	Choice of counter-productive goal
	Unnecessary	Choice of non-productive goal
	Lack	Goal not chosen
Choice of Procedure	Incomplete	Choice would not fully achieve goal
	Incorrect	Choice would achieve incorrect goal
	Unnecessary	Choice unnecessary for achieving goal
	Lack	Procedure not chosen
Execution of Procedure	Omitted	Required step omitted
	Repeated	Unnecessary repetition of required step
	Added	Unnecessary step added
	Sequence	Required steps executed in wrong order
	Timing	Step executed too early or too late
	Discrete	Discrete control in wrong position
	Continuous	Continuous control in unacceptable range
	Incomplete	Stopped before procedure complete
	Unrelated	Unrelated inappropriate step executed

Table 2   Rouse and Rouse Error Classification Scheme (continued) [16]

Error Cause/Contributory Factor	Examples
Inherent Human Limitations	levels of training/experienc interpersonal relationships complacency over-confidence motivation
Inherent System Limitations	maintainability of individual components (layout, access, workspace, etc) design of procedures/instructions utility and ease of use of tools
Contributory Conditions	working environment (noise, vibration, temperature, weather, etc) workload (physical and mental)
Contributory Events	distractions degradation in communication equipment failure unavailability of tools/spare parts