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RISK BASED LIFE MANAGEMENT OF OFFSHORE STRUCTURES AND EQUIPMENT

By

Ujjwal R Bharadwaj
RISK BASED LIFE MANAGEMENT OF OFFSHORE STRUCTURES AND EQUIPMENT

By

Ujjwal Ramakant Bharadwaj

A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

[September 2010]
ACKNOWLEDGEMENTS

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This thesis presents research undertaken from 2006 to 2009 to fulfil the requirements of a Doctor of Engineering (EngD) degree at the Centre for Innovative and Collaborative Engineering (CICE), Loughborough University, UK. The CICE is one of the EngD centres through which the Engineering and Physical Sciences Research Council (EPSRC) operates its EngD programme. Funding for this research was obtained from EPSRC and TWI Ltd, the industrial sponsor of this doctorate, via the CICE.

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My wife, Mamta, has stood by me with uncomplaining patience. My daughter, Khushi, born last year is an untiring source of happiness to me. Thanks to these two very special persons in my life.

2010
ABSTRACT

Risk based approaches are gaining currency as industry looks for rational, efficient and flexible approaches to managing their structures and equipment. When applied to inspection and maintenance of industrial assets, risk based approaches differ from other approaches mainly in their assessment of failure in its wider context and ramifications. These advanced techniques provide more insight into the causes and avoidance of structural failure and competing risks, as well as the resources needed to manage them. Measuring risk is a challenge that is being met with state of the art technology, skills, knowledge and experience.

The thesis presents risk based approaches to solving two specific types of problem in the management of offshore structures and equipments. The first type is finding the optimum timing of an asset life management action such that financial benefit is maximised, considering the cost of the action and the risk (quantified in monetary terms) of not undertaking that action. The approach presented here is applied to managing remedial action in offshore wind farms and specifically to corroded wind turbine tower structures. The second type of problem is how to optimise resources using risk based criteria for managing competing demands. The approach presented here is applied to stocking spares in the shipping sector, where the cost of holding spares is balanced against the risk of failing to meet demands for spares.

Risk is the leitmotiv running through this thesis. The approaches discussed here will find application in a variety of situations where competing risks are being managed within constraints.
KEY WORDS

Risk management, asset life management, risk based inspection, maintenance, spares inventory management, decision-making, simulation, probabilistic models, optimisation, reliability.
PREFACE

The thesis presents research conducted from 2006 to 2009 under the Engineering and Physical Sciences Research Council (EPSRC)’s Doctorate of Engineering (EngD) scheme. The thesis fulfils the requirements of an EngD degree at the Centre for Innovative and Collaborative Engineering (CICE) at Loughborough University, one of centres operating the EPSRC’s EngD scheme. The research was based at TWI Ltd, Cambridge, the industrial sponsor of the doctorate. Funding for the research was obtained from EPSRC and TWI Ltd, Cambridge.

At the core of the EngD is the solution to one or more significant and challenging engineering problems within an industrial context. The thesis here has an underlying theme of risk based approaches to decision-making with reference to life management of assets. Risk based approaches as applied to the life management of offshore wind farms and spares inventory management are discussed in the thesis. There is a collection of technical papers appended to this thesis. The papers form an integral part of the research and should be read in conjunction with the main text. The papers are referenced from within the discourse wherever required.
USED ACRONYMS / ABBREVIATIONS

AIM Asset Integrity Management
API American Petroleum Institute
ASME American Society of Mechanical Engineers
BSI British Standards Institution
CCS Carbon Capture and Sequestration/ Storage
CICE Centre for Innovative and Collaborative Engineering
CIRIA Construction Industry Research and Information Association
DCC Discounted Cash
DNV Det Norske Veritas
DTI Department of Trade and Industry, UK
EEMUA Engineering Equipment and Materials Users’ Association
EngD Doctor of Engineering
EOQ Economic Order Quantity
EPSRC Engineering and Physical Sciences Research Council
ESIA Engineering Structural Integrity Assessment
ETA Event Tree Analysis
EV Expected Value
FABIG Fire and Blast Information Group
FFS Fitness for Service
FMEA Failure Modes and Effects Analysis
FMECA Failure Modes and Effects Criticality Analysis
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>FPSO</td>
<td>Floating Production, Storage and Offloading</td>
</tr>
<tr>
<td>FTA</td>
<td>Fault Tree Analysis</td>
</tr>
<tr>
<td>GADS</td>
<td>Generating Availability Database System</td>
</tr>
<tr>
<td>HAZOPS</td>
<td>Hazard and Operability Studies</td>
</tr>
<tr>
<td>HSE</td>
<td>Health and Safety Executive</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technologies</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electro technical Commission</td>
</tr>
<tr>
<td>IET</td>
<td>Institute of Engineering and Technology</td>
</tr>
<tr>
<td>IF</td>
<td>Impact Factor</td>
</tr>
<tr>
<td>IMECE</td>
<td>International Mechanical Engineering Congress and Exposition</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>JIT</td>
<td>Just-in-time</td>
</tr>
<tr>
<td>MCS</td>
<td>Monte Carlo Simulation</td>
</tr>
<tr>
<td>MRP</td>
<td>Materials Requirement Planning</td>
</tr>
<tr>
<td>NDT</td>
<td>Non Destructive Testing</td>
</tr>
<tr>
<td>NERC</td>
<td>North American Reliability Corporation</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operation and Maintenance</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>OMAE</td>
<td>Offshore Mechanics and Arctic Engineering</td>
</tr>
<tr>
<td>PAS</td>
<td>Publicly Available Specification</td>
</tr>
<tr>
<td>RBI</td>
<td>Risk Based Inspection</td>
</tr>
<tr>
<td>RBLM</td>
<td>Risk Based Life Management</td>
</tr>
<tr>
<td>RCM</td>
<td>Reliability Centred Maintenance</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>RISPECT</td>
<td>Risk Based Expert System for Through-Life Structural Inspection, Maintenance and New-Build Structural Design</td>
</tr>
<tr>
<td>RL</td>
<td>Remaining Life</td>
</tr>
<tr>
<td>RM</td>
<td>Reactive Maintenance</td>
</tr>
<tr>
<td>RPM</td>
<td>Risk Priority Measure</td>
</tr>
<tr>
<td>TRV</td>
<td>Total Risk Value</td>
</tr>
<tr>
<td>TSC</td>
<td>Total Stock Cost</td>
</tr>
<tr>
<td>WT</td>
<td>Wind turbine</td>
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LIST OF PAPERS

During the course of research for this thesis, the following papers have been produced in partial fulfilment of the EngD award requirements:

PAPER 1 (APPENDIX A)


PAPER 2 (APPENDIX B)


PAPER 3 (APPENDIX C)


PAPER 4 (APPENDIX D)

Bharadwaj, U.R., Silberschmidt, V.V., Wintle, J.B “A risk based approach to asset integrity management”, accepted for publication in the Journal of Quality in Maintenance Engineering. (This paper is an extension of Paper 1 in Appendix A)
1 INTRODUCTION

1.1 THEME

This thesis describes research relating to risk based life management of offshore structures and equipment. The kinds of offshore structures being considered include ships and tankers, oil rigs, subsea pipelines and other types of offshore installation and equipment such as FPSO (Floating Production Storage and Offloading) vessels, offshore CCS (Carbon Capture and Storage/Sequestration) depots and offshore wind farms. The efficient management of these structures and equipment during their life to ensure fitness-for-service with optimum financial return on investment is an important duty for owners and operators.

Offshore structures and equipment are often complex and operate in a hostile environment. They may be more susceptible to failure and their failure may have different implications in relation to that of their on-shore counterparts. These aspects mean that processes for life management established for on-shore structures and equipment may not be applicable to structures and equipment offshore, where a different treatment might be more appropriate.

Life management includes all activities that can affect the life of an asset such as: design, manufacturing quality, operations, monitoring, integrity assessment, inspection, maintenance, repair, refurbishment, renewal, upgrading, replacement and decommissioning decisions. There is a continuum of approaches to life management requiring increasing levels of information and discrimination: the run-to-failure (and replace) approach at one end of the spectrum, to the relatively more advanced risk based approach at the other end of the spectrum. There are intermediate approaches such as reactive maintenance, rule-based (or

* In this thesis, for convenience, this often repeated term is used without the hyphen as in ‘risk-based’.
time-based) and condition-based approaches. The relatively recent risk based approaches are driven by industry needs for a more flexible, efficient, and rational basis to life management.

1.2 AIM AND OBJECTIVES

The aim of the research described in this thesis is to develop new methods for the life management of assets using risk based principles, with particular application to offshore structures and equipment. This aim has been achieved through specific projects at TWI, two of which are described in this thesis. These two projects and their objectives are as below.

- The first project develops a risk based approach to the life management of offshore wind farms. Here, the objective is to find the optimum time of repairing/ replacing a degraded structure identified as high risk so that the long term financial benefit is maximised, taking into account the expected failure rate and a number of constraints. The method is demonstrated using the wind turbine tower structure as the component at risk of failure due to the action of a specific damage mechanism - corrosion.

- The second project develops a risk based approach to spares inventory management such that the costs involved in holding spares and the risks involved in not doing so are within user specified constraints. Here, the objective is to find the optimum level of spares of different kinds an industrial enterprise should advance order given that failures (requiring these spares) may occur in service. The application of this approach is to a fleet of cargo ships where parts of different kinds are required to be stocked to keep ships available for service.

1.3 THE STRUCTURE

The structure of the thesis, chapter 2 onwards, is depicted in figure 1-1.
Chapter 2 sets out the common risk based attributes of the methodologies described in the sections that follow. It starts with introducing the terms and concepts used in this work: there is a description of risk in its broadest sense; this is followed by a discussion on risk based principles, life management of assets and the characteristics of offshore structures and equipment.

It then discusses risk based approaches as applied to life management including the planning of inspection and maintenance. The reasons why the bathtub curve, widely used in reliability engineering, often with some modification, provides a theoretical framework for life cycle management of assets is then discussed. The chapter refers to appendix E which contains further details of topics mentioned in the text. Appendix F contains a discussion of the risk matrix technique of qualitative risk analysis.

Chapters 3 and 4 describe two projects that are central to the research described in this thesis. In figure 1-1, these are shown in highlighted boxes.

- Chapter 3 describes parts of a project on risk based life management of offshore wind turbines. This project developed a risk based life management methodology to find the optimum trade-off between run-repair-replace costs and the expected cost of failure in offshore wind farms, and produced prototype software to implement the same. In this thesis, the focus of discussion is the risk based run-repair-replace decision-making methodology aimed at maximising the net present value (NPV) of the investment. For demonstration, the methodology has been applied to address corrosion of the tower structure. There are two appendices referred to in Chapter 3.
  - Appendix A is a paper on this project presented at the 2007 Offshore Mechanics and Arctic Engineering (OMAE) Conference.
  - Appendix G describes wind turbines.
• Chapter 4 describes a project to develop a risk based spares inventory management system. In this project, a model for managing risk was developed to find the optimum level of spares of different kinds a major industrial enterprise should advance order given that failures requiring these may occur in service. The particular application was a fleet of cargo ships where parts of different kinds are required to keep ships available for service. There are two appendices relating to this project.

  o Appendix B is a working paper presented at the 2008 International Mechanical Engineering Congress and Exposition (IMECE), USA.

  o Appendix C is a paper, describing further progress, presented at the 2009 Engineering Structural Integrity Assessment (ESIA-10) conference, Manchester, UK.

Chapter 5 discusses the salient common features in the application of the risk based approaches presented in the previous chapters and comments on their uptake and relevance. The practical issues in applying the research and possibilities for further work are also considered.

Chapter 6 sums up the thesis with concluding remarks.

1.4 OTHER RELEVANT STUDIES

The research presented here is directly or indirectly influenced by

• Courses undertaken:

  o MSc level course ‘Renewable Energy Technology’ at Cranfield University, 2006.
o MSc level course ‘Structural Analysis’ conducted by Professor Silberschmidt (completed Feb, 2008) at Loughborough University.

o ‘Research, Innovation and Communication’ module offered to doctoral candidates at Loughborough University.

- Conferences attended/ presented at:


  o Attendance at ‘Risk Analysis and Structural Reliability’ course at MARSTRUCT, Glasgow, and 20- 22 of November 2006.


  o Conference paper presentation: ‘A Risk Based Methodology for Spare Parts Inventory Optimisation’, ASME IMECE conference, 3 -6 Nov 2008, Boston, USA.

- Supervision:
  - Professors Vadim V Silberschmidt (Loughborough University) and John D Andrews (previously at Loughborough University).
  - John B Wintle (TWI Ltd) and Julian B Speck (previously with TWI Ltd).

### 1.5 INDUSTRIAL HOST: TWI LTD

TWI Ltd is the industrial host of this engineering doctorate. TWI Ltd is an independent, not-for-profit distributing, membership-based, engineering research and consultancy organisation. TWI's mission is to deliver world-class service in joining materials, engineering and allied technologies to meet the needs of a global membership and its associated community.

This research draws heavily on my work done within the Asset Integrity Management section of the Structural Integrity Technology Group (SITG) at TWI Ltd, Cambridge where I have been based. The Asset Integrity Management section provides a variety of services to the petrochemical and process industry. These services include: providing consultancy for optimising inspection and maintenance, implementing risk based management principles, assessing fitness for service (FFS) against code requirements, and providing plant integrity courses in FFS, Risk Based Inspection (RBI), degradation and repairs.
Technical papers:
Appendix A: A practical approach to risk based assessment and maintenance optimisation of offshore wind farms.
Appendix B: A risk based methodology for spare parts inventory optimisation.
Appendix C: Optimisation of resources for managing competing risks.
Appendix D: A risk based approach to asset integrity management.

Figure 1-1: Structure of the thesis
2 RISK BASED LIFE MANAGEMENT OF ASSETS

2.1 FUNDAMENTAL CONCEPTS AND DEFINITIONS

2.1.1 THE NATURE OF RISK

Risk is an intangible concept. It can be looked at from various perspectives and has connotations depending on the context in which it is used. From one perspective it is a combination of the probability of harm and the severity of that harm (ISO/IEC Guide 51:1999 1999).

A more encompassing description of risk is obtained by considering it to be inherent in any action and, indeed, inaction. Many organizations increasingly apply risk management to optimise the decisions regarding potential opportunities that need to be acted upon. In this sense, risk has a broader meaning than mentioned above. The ISO/IEC guide on risk management vocabulary defines risk as the combination of the probability of an event and its consequence (PD ISO/IEC Guide 73:2002 2002). The document notes that risk is generally used only when there is at least a probability of negative consequences, and in some situations, risk arises from the possibility of deviation from the expected outcome or event.

This description of risk is all including: most actions do have potentially negative consequences; actions often assume normal conditions, deviations from which result in outcomes that are different from what was expected. Where quantitative risk modelling is involved, normal conditions may entail mean values (in statistical terms). Deviations from normal, or the degree of (or the lack of) confidence in input values to the model, may depict risk.
In the context of this thesis, ‘risk’ is used in its broadest sense, to mean the combination of the probability of an event and its consequence. The consequences are usually negative and quantified in some way.

Risk is a complex entity: it cannot be measured easily as it involves probability and prediction. There are two components to our inability to precisely determine risk—these are variability and uncertainty in the inputs to risk analysis. Variability, also called as “aleatory uncertainty” or “stochastic variability”, is the effect of chance and is a function of the system, not reducible through further study or further measurement, but may be reduced by changing the physical system. Uncertainty, also called as “epistemic uncertainty” or “fundamental uncertainty” is the assessor’s lack of knowledge (level of ignorance) about the parameters that characterise the physical system that is being modelled (Vose 2008).

The comment made in a political risk management context offers another perspective “There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know” (Rumsfeld 12 February 2002). Unknown unknowns are the result of total ignorance. Known unknowns can be construed as knowing the variability in the inputs, at best, or, at least knowing that certain variables affecting the outcome are likely to change in ways not easily foreseeable. Taleb calls unpredictable events ‘Black Swans’ and suggests that instead of trying to predict them in vain, we need to adjust to their existence (Taleb 2007).
2.1.2 **MEASURES OF RISK**

Whilst accepting that the inputs to risk analysis may not always be precise or definite or, indeed, lacking (not available) or retrospectively (post-event) realised as missing (not conceived of), this thesis does not dwell on the moot issues relating to forecasting or prediction. Research presented here is more influenced by the study of the management of risk than by the study of risk: the focus is on how to make the best use of available information in the management of risks.

Probability or likelihood, mentioned above, is the extent to which an event is likely to occur. Mathematically, probability is a real number between 0 and 1 indicating the occurrence of a random event. It can be related to the long-run relative frequency of occurrence or to a degree of belief that the event will occur. Degrees of belief about the likelihood of an even can also be expressed in classes or ranks such as Very Low, Low, Medium, High and Very High.

Consequence is the outcome of an event (an occurrence of a particular set of circumstances). Consequences can be positive or negative but are always taken as negative in a safety context. As in likelihood or probability, consequences can be quantitative or qualitative.

In the context of this thesis, risk will involve the probability or the likelihood of failure of a component or a system of components to fulfil its design purpose in a given time frame and under given operating conditions. Where the two components of risk i.e. the likelihood and the consequence of a failure event are quantitatively expressed, risk will be expressed in terms of ‘expected loss’. Expected loss can be defined quantitatively as the product of the
consequences (C) of a specific incident and the probability (P) over a time period or frequency of its occurrence (Andrews, Moss 2002):

\[ R = C \times P. \]  \hspace{1cm} (2.1)

Qualitatively, a set of events can be graded depending on their likelihood and the impact of their occurrence. The risk matrix technique, discussed later on, is mainly a qualitative one, although it can have quantitative values.

The risk of an event, expressed qualitatively (High, Medium, Low, for example) or quantitatively (in absolute terms), is often evaluated as relative to some other event. For example, the risk (of death) posed by a particular surgery may be compared to the risk of death by accident prevalent in the area; indeed, it may also be compared to the risk of not undergoing surgery.

Risks here broadly fall in the following three categories: Occupational risks that impact personnel engaged in industry; Societal risks that impact the people and the environment; Financial risks that arise from loss of capital assets, production and compensation.

2.1.3 **Risk Management**

Risk management is coordinated activities to direct and control an organization with regard to risk. It includes risk assessment which is the overall process of risk analysis and risk evaluation. Risk analysis is the systematic use of information to identify sources of risk and to estimate it. Risk evaluation is the process used to compare estimated risk against given risk criteria to determine the significance of risk (API 2002a).
2.2 ASSETS AND THEIR MANAGEMENT

2.2.1 OFFSHORE STRUCTURES AND EQUIPMENT

Ships and tankers, offshore oil rigs, sub sea pipelines and other offshore installations such as FPSO (Floating Production Storage and Offloading) vessels, offshore CCS (Carbon Capture and Storage/ Sequestration) depots are all offshore structures or equipment. These differ from their counterparts on land in a number of ways: one crucial difference is that the nature of risk, in terms of both the likelihood of failure and the consequences of the same, offshore is different to that onshore.

Often offshore structures are complex, large and operate in a hostile environment. Without life management, they are more susceptible to failure. At times they have a higher degree of novelty than onshore structures. Some structures, for example, FPSO vessels, are often converted ships not designed for this new purpose and need special attention; some of their design aspects may be outside Class rules.

In terms of occupational risks, for serious crises personnel offshore have more limited escape routes and need to rely on support from land that might not be forthcoming for a variety of reasons. Societal risk, in case of offshore structures is usually restricted to the marine environment. However, there are instances where pollution has affected people in coastal areas. Breakdowns at sea often take longer to rectify: they may entail waiting for suitable weather windows or dry docking a ship, for example. Thus there is often a prolonged period of production loss leading to financial loss.
The nature of risk for different structures differs: ships may be able to change course to avoid extreme loading, whereas fixed structures such as oil rigs may be subject to more extreme loading. Wind turbine structures are fixed but carry a rotating wind turbine adding to the type of loading normally experienced by offshore structures. Some structures like oil rigs may have a contingent of personnel whereas others such as wind farms are usually unmanned.

2.2.2 ASSET MANAGEMENT

Asset integrity management (AIM) includes all actions that enable an asset to perform its function effectively and efficiently whilst safeguarding life and the environment. ‘Asset integrity management ensures that the people, systems, processes and resources which deliver integrity are in place, in use and fit for purpose over the whole life-cycle of the asset. The objectives of an AIM system are the delivery of business requirements to maximise return on assets, whilst maintaining stakeholder value and minimising business risks associated with accidents and loss of production’ (Bureau Veritas).

There are various documents pertaining to the practice of AIM. In response to demand from industry for a standard for asset management, there is a publicly available specification (PAS) first published in 2004 and superseded in 2008. The document (BSI 2008) lists terms and definitions, and provides a framework for AIM. Another good practice guide in asset management is by CIRIA (Construction Industry Research and Information Association) (CIRIA 2009).

The objectives of AIM mentioned above are typical in the engineering industry. As is evident, AIM usually includes both safety and reliability driven risk management as well as commercially driven risk management. This is in contrast to practices in the financial sector where risk management is usually purely driven by commercial or business considerations and indeed, the metrics used to measure such risk reflects this.
2.2.3 THE PRACTICE OF ASSET MANAGEMENT

The practice of asset integrity management is not new. However, it is only recently that it is increasingly being recognized as a distinct set of business processes, disciplines and professional practices. This recognition is in no small part due to the complexity of the assets and the linkages between various asset systems created in industry- such systems require a holistic/ integrated view for them to operate safely and efficiently.

Factors such as more experience in operating assets, a better understanding of failures, more computing power to create and run sophisticated models, IT systems and better condition monitoring techniques are helping in increasing the effectiveness of asset integrity management.

Within asset management, there are strategies and techniques to implement these strategies. For example, risk based inspection (RBI) is a strategy and some of the tools to implement this strategy are simulation, HAZOPS, Probabilistic analyses, and FFS assessments. There are a number of commercially available tools to provide inputs or to aid decision making in asset management. For example, there are tools developed by Decision Support Tools Ltd such as APT© (Asset Performance Tools) toolkits developed for Inventory and purchasing decisions, maintenance/ inspection scheduling, etc.). SIL (Safety Integrity Level) assessments are formal classification methods that provide a record of a quantified assessment of the probability of failure on demand of a safety system taking into account the consequences of such failure. SILs often form a part of a Quantitative Risk Assessment (QRA) that is then fed into a decision-support tool. TWI has Riskwise© software aimed at implementing risk based approaches (following various ASME/ BSI codes or bespoke practices) in the inspection and maintenance of assets such as power plants, refineries and pipelines.
The discussion above and in previous sections shows that asset management requires people who can take a wider multi-disciplinary perspective. Apart from engineering knowledge and skills, an awareness of the larger context in which an asset is operating is often required. As pointed out by the Woodhouse Partnership, asset management needs skills such as reliability and maintenance engineering, root cause failure analysis, life cycle costing, project/ change management that have traditionally not been the focus of engineering degrees (The Woodhouse Partnership Ltd, 2008). However, now distinct engineering disciplines such as systems engineering, reliability engineering and operations management are dedicated to looking at these aspects in greater detail.

2.2.4 LIFE MANAGEMENT OF ASSETS

‘Equipment or structure begins to age as soon as it is built. Cyclic stresses cause fatigue and looseness. High temperature causes creep. Erosion and corrosion cause thinning and weakening. Thus age in many ways degrades, deteriorates and destroys’ (ASME International 2003a).

Life management includes all processes that manage the ageing of assets during their life. The HSE report on plant ageing (Wintle et al. 2006) segments ageing management into:

(a) Setting up an organizational structure to manage ageing

This includes taking responsibility for and control of the process of managing assets, establishing a company culture, strategy, systems for knowledge management and retention,
and taking care of human factors such as competencies required, training, succession planning etc.

(b) Identification of ageing

This includes establishing damage types and mechanisms, assessing the rate and accumulation of damage, assessing age related risk factors, and inspection and non-destructive testing.

(c) Addressing ageing

This includes assessing fitness-for-service and remaining life. Fitness-for-service of an asset is its adequacy to meet specified performance criteria for a period of continued service taking into account degradation and other changes that may have occurred or that are postulated to occur in future. Maintenance, repair and modifications, revalidation of equipment, planning for spares, reviewing schemes of examination and condition monitoring, and determining the end of equipment life, usually using a financial criterion, are also part of ageing management.

‘Ageing’ in the current context is the process of deterioration and damage taking place since the equipment or structure was new. Ageing may not necessarily be a symptom of old age. Relatively new equipment may have undergone more ageing than equipment that was put into service earlier. Assessing ageing- knowing the current state of assets and assessing future condition, bearing in mind the factors that influence the onset, evolution and mitigation of degradation- is a very significant part of life management.
Assessing ageing for life management poses challenges to those responsible for it: different components (of a system) age differently and at a different rate; a single component may age differently and at a different rate over a period of time; the consequences of failure of one component may be different to those of another; and, different components may have different costs and techniques associated with managing them. Thus there are competing risks of failure and finite resources to manage them. Moreover, in certain situations, condition monitoring and inspection, the two main inputs to risk analysis within life management may not be achievable effectively and with precision.

Life management of assets is a critical activity: it can optimise performance within constraints such as costs, reliability and safety. It has a direct bearing on the availability of assets for production.

2.2.5 ROLE OF INSPECTION AND MAINTENANCE IN LIFE MANAGEMENT

It is necessary to assess Ageing to establish the state or condition of equipment that could justify its continued service, re-rating, repair, or scrapping. Inspection provides information regarding the current state of equipment. This information is helpful in reassessing risk. For example, inspection may reveal that a particular damage rate is more than initially assumed in a risk assessment leading to revised estimates. Inspection per se does not reduce risk: it is an integral part of risk management that may lead to risk reduction by informing further action such as maintenance and repair. The risk based inspection planning process followed by API (API 2002b) is shown in figure 1-2.
Maintenance includes all activities that sustain or protect equipment for it to remain fit for service. In terms of the bathtub curve discussed in the next section, maintenance prolongs the useful life of equipment.

![Figure 2-1: Risk based inspection planning process (API recommended practice 580)](image)

### 2.2.6 DIFFERENT APPROACHES TO LIFE MANAGEMENT

Whilst there remains a need for traditional approaches to inspection and maintenance, it is increasingly felt that more advanced approaches are required. This is mainly due to two reasons:

(a) To reflect the complexity and innovation involved in the assets. It is often seen that there are complex systems within systems with a lot of interaction between them. The innovation within systems means that experience based information - the main input to time based inspection and maintenance - is not available. For example, in the shipping industry, some aspects of design may fall outside the remit of traditional Class rules (that are experience based).

(b) To operate at an optimal level within the competitive pressures faced by asset managers.
The more advanced approaches, as opposed to the rule-based or time-based traditional approaches, give operators some flexibility in the management of their assets whilst meeting the same objectives. The flexibility is as a result of undertaking actions not on a fixed schedule, but on factors such as the condition of the asset (symptoms of ageing). The risk based approach uses risk based criteria to prioritize efforts and make the optimum use of this flexibility.

Generally, in refining and chemical process plants, a relatively large portion of risk is concentrated in a smaller percentage of equipment (API). It thus makes sense to focus resources on the high risk components of a plant. It must be noted the development of such condition based approaches to AIM has been aided, in no small measure, by advances in NDT and information and communication technology.

Inspection and maintenance strategy have followed an evolutionary continuum from the more time based traditional approaches to the advanced ones such as risk based (figure 2-2, adapted from (Lee et al. 2006)).

![Figure 2-2: Continuum of approaches leading up to risk based approaches](image-url)
The figure above shows some attributes of the main approaches to life management.

- Time-based approaches are those in which specified action is required at some point of time; often there are industry standards stipulating when or how frequent the action is required. The approach is also called the rule-based approach as this approach is prescriptive and the scheduling of the concerned action is not at the discretion of the operator. These rules or standards are based on industrial experience and are influenced by historical data; in this sense, the rules assume that the asset is operating in industry-wide average conditions.

- Condition-based approaches are those in which action is informed by the condition of the asset. Relative to the rule-based approach, the approach here is more case-by-case, i.e., based on current state of the asset and on local conditions.

- The more advanced risk based approach prioritises action based on the risk profile of various components within a system; the aim here is to focus resources on the components that are deemed more risky. Relative to other approaches, this is a more sophisticated approach to asset management in that, apart from factors considered in the previous approaches, here the context in which the asset (or a component within a system) is being operated is also considered.

Risk based approaches in a way often add a third dimension to failures. Apart from the likelihood and consequence of failures, these approaches, by focussing resources on high risk components, consider the manageability aspects of failures within resource constraints. These approaches often answer the question: how to best manage the risk from failures within a system of components, given the resources available?

In the interest of continuity, mention must be made of some other approaches, each having their own bias. Reliability Centred Maintenance (RCM) is a subset of risk based maintenance
in that maintenance is optimised taking into consideration the effect the equipment has on plant reliability. Here, reliability can be quantitatively expressed as the probability that an item (component, equipment, or system) will operate without failure for a stated period of time under specified conditions. Reactive Maintenance (RM) is an approach in which maintenance is performed only when the machine fails or shows signs of failing. Run-to-failure policy is one in which the equipment is run until it breaks down effecting RM or resulting in discarding the equipment, for example, a satellite.

The above discussion shows that the level of sophistication in various approaches to maintenance (asset life management, in general) increases from the run-to-failure policy to the risk based approach.

2.3 RISK BASED APPROACHES TO LIFE MANAGEMENT

2.3.1 BACKGROUND

Increased competition is a major driver for cost effective approaches to the life cycle management of assets. One such approach is the risk based approach where ‘risk’ involves the likelihood of failure of an equipment, component, or structure to fulfil its function and the consequential impact of such a failure.

Life cycle management is particularly crucial for a plant in the Useful stage and the Ageing stage of its life cycle as depicted in the classic bathtub curve shown in figure 2-3. Figures 2-4 and 2-5 have been adapted from the HSE report on plant ageing (Wintle et al. 2006). The bathtub curve is the idealized curve of the failure rate within a system of infinite components versus operating time. Depending on the failure rate, different phases can be discerned in the
lifetime of a system. There are no fixed demarcations between these stages. Indeed, two systems commissioned together may be in different stages of their life cycle.

Stage 1: ‘Infant Mortality’

As a system is put into service, initially the failure rate is high because of the so called ‘teething’ problems (figure 2-3). The high failure rate during this stage could be because of one or the combination of the following:

--- Early ‘infant mortality failure’ rate
--- Wear-out failure rate
--- Constant (random) failure rate

Stage I: Infant mortality
Stage II: Useful life
Stage III: Ageing

The curves in the figure do not use the same scale.

Figure 2-3: The bath tub curve and its components
Figure 2-4: Variation in accumulated damage during equipment cycle

Figure 2-5: Effect of periodic maintenance, inspection and repair on the risk of failure

(Each saw-tooth represents an inspection being carried out on the piece of equipment; figures 2-3, 2-4 and 2-5 are not drawn to the same scale)
• Incorrect application

• Installation flaws

• Inherent weakness in component design and material that manifests itself as a failure when service conditions are experienced initially

• Fabrication defects not identified by Quality Control/Manufacturing NDT or inspection

Some of these issues can be remedied at the first examination normally carried out within the initial years of operation. The first examination can be used to confirm the reported as-manufactured condition, and to provide a benchmark against which damage found in future examinations could be assessed for life predictions.

Run-repair-replace decision making as part of life management, in the current context, focuses on the stages that follow this initial post commissioning stage. This is because unlike the initial post commissioning stage in which failures are due to teething problems, in other stages most of the failures (not counting random failures) are attributable to the action of in-service damage mechanisms.

Stage 2: Useful life

As the name suggests this is the most productive stage of the system. Teething problems have been identified and fixed and the equipment is predictable, reliable and has a low rate of failure or issues requiring attention. Inspection and maintenance is aimed at prolonging the useful life stage of a system.
Stage 3: Ageing

By this stage the equipment is nearing the end of the low damage rate phase. Damage accumulated in the previous two stages manifests itself in as an increasing failure rate. At this stage, run-repair-replace decisions entailing a more proactive approach towards inspection, fitness for service and remnant life assessment of the component needs to be taken.

From the viewpoint of accumulated damage (figure 2-5), equipment in Stage 1, when new or after repairs, manufacturing or installation, may contain defects that may trigger an increased rate of degradation during service. In Stage 2, although failure rates are nearly constant, damage is accumulating. This accumulated damage manifests itself in an increasing failure rate in Stage 3.

2.3.2 Factors Influencing the Bath Tub Curve

There are practitioners who find the bath tub curve elusive to observe in practice. This could be due to the following reasons:

- The bath tub curve has its origins in reliability studies in the electronics industry. A system of electronic components does not normally undergo the sort of inspection and maintenance that other engineering structures/equipment would. Figure 2-3 shows the effect of inspection, maintenance and repairs on the risk of failure.

- The rates of degradation may be highly variable and non-linear depending on the degradation mechanism and local operating conditions. On the one hand wall thickness due to corrosion may proceed at a constant rate (though not always), on the other hand, the number and size of creep and fatigue cracks and local corrosion tend to accelerate with time. There can be circumstances where the rate of degradation slows and even stops.
Corroding areas may build a layer of oxide that inhibits further attacks. Fatigue cracks may stop growing for sometime if subjected to an overload.

A structure such as a ship may age differently with a change in the operating condition: for example, a change in cargo, or a change in route.

- The manner of operation, maintenance, inspection, and repairs has a bearing on the rate of degradation. An asset may change hands, or maintenance personnel may change resulting in a change in the manner an asset is operated and maintained. Invasive work can introduce contaminants into the system thereby increasing the rate of degradation, temporarily or in the long run. Appropriate inspection, maintenance, and repairs of damaged areas can reduce both the amount and the rate of change, while unnecessary work may have little benefit.

Notwithstanding the above factors, in the life cycle management of assets, it is often useful to assume that damage will accumulate over time and manifest itself in terms of an increasing failure rate (figures 2-3, 2-4, and 2-5). This provides a theoretical framework on which to build a strategy for asset management. It is worth noting here that wear (accumulating as a function of hours of use, severity of use, and level of preventive maintenance) and deterioration (the gradual decay, corrosion, or erosion as a function of time and severity of exposure conditions) of an asset are major factors leading to the loss in value of the same over a period of time (Collier, Glagola 1998). In accountancy, this loss of value is represented by depreciation of the asset over the time. Thus, during the ageing phase of an asset, and at times the useful phase, run-repair-replace decisions typically consider not just FFS assessments, but also financial implications such as the cost of equipment failure, the cost of new equipment, and the depreciation (in accountancy terms) calculated on the asset. The model in the next chapter
Risk Based Life Management of Offshore Structures and Equipment

considers these factors in the run-repair-replace decision making in the management of offshore wind farms.

Risk based maintenance approaches focus mainly on the useful and the ageing phases of a system. The assessment of risk forms part of what is known as asset management as discussed in chapter 1. The aim of risk based asset management is to assist companies in adopting a holistic approach to improve performance, dealing not only with the technical or commercial risks themselves but also the context in which they exist.

2.3.3 The Concept of Target Risk/Reliability Levels

Activities such as inspection, maintenance and repair aim at maintaining assets within identified acceptable risk/ reliability levels. Figure 2-6 shows the main approaches to establishing what acceptable level of risk / reliability is.

Figure 2-6: The approach to establishing acceptable risk/reliability levels

1) Agree upon reasonable value in cases of novel structures
2) Calibrate levels implied in currently successful design codes
3) Minimise total expected cost over service life of the structure – used mainly for failures resulting in economic consequences
The first approach can be based on expert-opinion elicitation for want of real data or experience in operating the new type of structure/equipment. There are formal procedures for doing this (O’Hagan, Anthony et al, 2006; Ayyub, Bilal M, 2001).

The second approach, i.e. calibration to existing successfully used design codes, is the most commonly used approach as it provides the means to build on previous experiences (Ayyub, Bilal M., 2003). For example target reliabilities can be established by assessing those implied in current codes or rules provided by classification bodies and industry societies in similar applications.

The third approach is based on finding the optimum trade-off between the economic costs of an action that mitigates risk and the cost (risk of failure) without that action. Here the aim is to minimise the total ‘expected cost’ of operating a plant (structure/equipment). The next chapter shows how ‘expected cost’ is a useful measure of risk.

The approaches are by no means always mutually exclusive in their application. The risk based approaches described in the following chapters aim to minimise expected costs while remaining within certain constraints including stipulated reliability/risk levels.

2.3.4 GENERAL METHODOLOGY FOR RISK BASED LIFE MANAGEMENT

This section discusses main features of a typical Risk based Life Management (RBLM) approach which includes the following:

- System analysis
- Qualitative risk assessment
- Quantitative risk analysis
• Optimising inspection and maintenance

(a) System analysis

System analysis identifies system or subsystem components, boundaries and success criteria to be considered by the RBLM process being developed. It assembles, correlates and analyses system operation and failure information.

Once system components are identified, boundaries established and success criteria defined, there are a number of formal procedures that facilitate understanding potential failures within the system. The objective here is to highlight components that are relatively more at risk of failure. Some of these techniques are discussed below. These techniques are not rigid in their structure: there are many variants depending on the situation in which they are used.

High risk components that require more consideration need to be identified by formal engineering analyses techniques such as FMEA, FMECA, FTA and ETA. Failure Modes and Effects Analysis (FMEA) identifies the component failure modes and impacts on the surrounding components and the system. Failure Modes and Effects Criticality Analysis (FMECA) is an extension of FMEA in that it formally, qualitatively or quantitatively, ranks components in terms of their relative failure criticality. Fault Tree Analysis (FTA) is a graphical model created by reasoning that considers various combinations of events leading to the occurrence of some top event failure. Event Tree Analysis (ETA) is again a graphical model but is created by reasoning that considers initial events followed by other events leading to a final set of consequences. These techniques may be purely qualitative or may have some quantitative data too. Each of these techniques has advantages and limitations vis-à-vis others. Tools such as FMEA, FTA and ETA provide different perspectives on risk and
are not competing tools; they often act in conjunction with each other to give a larger picture of risk. Appendix E gives more details about the techniques discussed above.

(b) Qualitative risk analysis

Qualitative risk analysis is a technique of setting priorities by risk ranking system components into broad failure likelihood and consequence bands. The rankings are relative and based on the risk perception gained by experience or historical data captured by formal engineering techniques such as FMEA, FMECA, FTA and ETA as discussed above. Qualitative assessment creates a risk matrix that enables decision-makers to focus on highest risk for further action. This is the first step in thinking in terms of risk rather than just the probability or consequence of failure in isolation. Again, as it is a qualitative assessment, consequences like safety and environmental damage that are not easily quantifiable, may be factored in. This stage will act as a screening stage focusing any further quantitative assessment on the higher risk components.

Appendix F describes the risk matrix technique which is a common qualitative risk analysis technique. In the appendix some variants of the risk matrix are also discussed- these are semi-quantitative risk assessments.

(c) Quantitative analysis

Quantitative analysis replaces to the maximum possible extent, the qualitatively assessed likelihood and consequence estimates with numerical failure probability and consequence cost values.
Quantitative analysis is an elaborate exercise and is usually undertaken only to analyse those components that are identified as high risk by qualitative analysis. Whilst consequence cost is relatively easy to quantify - in terms of repair/replacement cost, loss of revenue, etc., the likelihood (or probability) of failure of an asset over time is more complex to ascertain. Failure probability assessment is usually obtained from:

1. **Specific failure data** – data that is class specific or plant specific and is locally available. It may be the best source but may not be available and/or statistically significant.

2. **Generic failure data** - available from OEMs and industry experts, reflecting average operating conditions.


The quantitative analyses in the chapters that follow use mainly engineering analyses and generic data to arrive at the probability of failure of an asset over a period of time. Indeed, there are techniques such as those based on Bayesian statistics that can be used to combine or update data from various sources.

**(d) Optimising inspection and maintenance**

Optimising inspection and maintenance within RBLM involves finding the optimum trade off between the cost of undertaking an action (inspection, maintenance, repair or replace) and the risk of not taking that action expressed quantitatively in monetary terms or semi-quantitatively. The optimisation shown in the following chapters takes into account constraints such as the available budget, acceptable risk and reliability.
The chapters that follow have the same underlying theme- risk based optimisation in the life management of assets. Risk, as mentioned earlier, involves the likelihood of failure and the consequence of the same. Optimisation is finding the optimum trade off between the expected cost (the risk) of failure and the cost of mitigating that risk within user specified constraints such as acceptable risk level and the budget available.

Risk can be reduced to a specified acceptable risk level by reducing the likelihood of failure or the consequences of such a failure. This reduction or mitigation is achieved at a cost which in practice needs to be within a specific budget.

Risk based optimisation of a system is different to that of an individual component. Some risk values of individual components may rise when the system risk is optimised. Indeed, if a maximum acceptable risk value for each component is specified, then the system risk can be optimised such that both individual and the overall system risks are within acceptable levels. The chapter on optimising spares inventory contains more details regarding system and individual risks.

The risk based optimisation in chapter 3 is aimed at finding the optimum time of repairing or replacing an asset such that costs of doing so are balanced by the risks of not doing so.

The risk based optimisation in chapter 4 is aimed at maintaining an inventory of spares at an optimum level by considering the costs of stocking spares and the costs of failure to meet a demand for the spares.
3 PROJECT 1: RISK BASED LIFE MANAGEMENT OF OFFSHORE WIND FARMS

3.1 GENERAL APPROACH

3.1.1 SCOPE

This chapter describes a research project undertaken with the aim of reducing operation and maintenance (O&M) costs and increasing the operational reliability of offshore wind turbines. This is done by developing a Risk Based Life Management (RBLM) methodology for the operation and maintenance of offshore wind farms. This report uses the convention that the term ‘wind turbine’ refers to the entire installation and system (rather than just the turbine itself), and the term ‘wind farm’ to refer to a group of wind turbines operating together.

The approach taken in the development of the RBLM methodology included the following tasks:

- System analysis.
- Qualitative assessment.
- Quantitative analysis.
- Optimising inspection and maintenance.

These tasks are discussed from a generic viewpoint in the previous chapter. The discussion that follows in this chapter is regarding the application of the above to offshore wind farms, with focus on the use of quantitative analysis in optimising inspection and maintenance. Other tasks are briefly mentioned with links to relevant appendices for more details.

3.1.2 SYSTEM DESCRIPTION AND ANALYSIS

The task started with understanding wind turbines. This included tracing the evolution of modern wind turbines, identifying key components, and looking at recent development in wind turbines. The task involved (1) conducting a literature review, (2) surveying wind turbine reliability databases and (3) eliciting expert opinion.

Appendix G describes a review of literature to understand wind turbines.

The survey of wind turbine reliability databases (an exercise that included processing of data to extract relevant failure statistics) and the elicitation of expert opinion - experts from OEMs and wind turbine operators - is the topic of a confidential report not included in this thesis. However, an overview of publicly available reliability databases that were considered in the report is given below.

The survey of wind turbine reliability databases included the following:

i) WindStats:

WindStats Newsletter is a quarterly wind energy publication with news, reviews on wind turbine production and operating data from over 15,000 wind turbines. It publishes production and failure data of wind turbines from Denmark, Sweden and Germany.

ii) The REISI (Renewable Energy Information System on Internet) database from ISET (Institute fur Solare Enertieversorgungstechnik), University of Kassel, Germany in conjunction with ‘Wind Energy Report Germany 2005’:

50
ISET manages a central data base containing wind turbine operating data (from wind turbines funded under a project called ‘250 MW Wind’, and data from other turbines that is voluntarily reported).

The data collected and processed by ISET is commercially available for the benefit of wind turbine operators and other interested parties. The Wind Energy Report Germany is the 15th of the annually published operational results from the WTs included in the 250 MW Wind funding programme. The programme initially started as 100 MW Wind programme in 1989 and was later expanded to 250 MW in 1991. By 1996, 1500 WTs with a total rated capacity of 350 MW were included in the programme. This programme provides one of the most comprehensive long-term operating databases in the world. The WMEP aims to collect data in a statistically useful way and evaluate it using uniform criteria for the benefit of the wind energy sector in Germany and elsewhere.

iii) Data from Landwirtschaftskammer Schleswig-Holstein

In this database, output data and failures of all turbines in the Schleswig-Holstein province of Germany are collected and presented. Data from about 500 turbines (57% of which are larger than 500kW) for the years 1999 and 2000 was extracted from the publicly available DOWEC project report (DOWEC).

iv) Caithness wind farm information forum

The forum (Caithness, date unknown) lists documented cases of wind turbine “accidents” that are found and confirmed through press reports or official information releases from the 1970s till recently.

v) Information from ‘Guidelines on the environmental risk of wind turbines in the Netherlands’
This report (Braam, Rademakers, 2002) analyses over 200 severe incidents and accidents from Denmark, Germany and the Netherlands. The data represents about 43,000 turbine years and calculates the frequency of occurrence of events relevant to risk assessment.

The task resulted in identifying main components of wind turbines and parts more prone to failure and/or having relatively higher consequence of failure. However, formal categorisation of components depending on their risk of failure took place in the next step.

### 3.1.3 Qualitative Assessment

A qualitative risk assessment method specifically for wind turbine towers is captured in spreadsheet format, screenshots of which can be seen in the figures accompanying the text. The procedure for qualitative assessment is described below.

Table 3-3 presents a list of the main components that construct a wind turbine. The list, which can be customized for specific wind turbine designs, is created by conducting system analysis (as discussed above).

Each of the identified components are individually considered and ranked in qualitative terms based on two criteria i.e. the likelihood of failure and the severity of the consequence of failure. Various factors contributing to the likelihood of failure and consequences are considered to get an overall likelihood factor and consequence ranking in qualitative terms. Many of these factors can be assessed using techniques such as FMEA, ETA and FTA that have been discussed in the previous chapter and/or referred to in the Appendices.
Factors contributing to the failure likelihood include:

- Current condition of the component;
- Design life consumed;
- Number of active damage mechanisms;
- Estimated rate of damage;
- Efficiency of inspection;
- Loading conditions;
- Environmental conditions.

Factors contributing to the consequence of a failure include:

- Production loss (during downtime);
- Secondary damage (knock-on effects);
- Threat to personnel;
- Rectification costs;
- Impact on reputation;
- Redundancy.

This estimate is in qualitative terms and ranks from very low (VL) to very high (VH). (VL-very low, L- low, M medium, H- high and VH- very high) More ranks could be used to give the assessment further resolution if required. Likewise, more factors perceived to be affecting the ranking could be added to the work sheet.

A possible qualitative ranking scheme for estimating the failure probability for a component is shown below:
Table 3-1: Ranking scheme for likelihood ratings

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description (expected failure rate of the component)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>Failures continuously experienced</td>
</tr>
<tr>
<td>High</td>
<td>Failures occur frequently</td>
</tr>
<tr>
<td>Medium</td>
<td>Failures occur several times</td>
</tr>
<tr>
<td>Low</td>
<td>Unlikely but possible to occur during the lifespan</td>
</tr>
<tr>
<td>Very Low</td>
<td>Very unlikely; occurrence may not be experienced at all</td>
</tr>
</tbody>
</table>

A possible qualitative ranking scheme for estimating the severity of the consequence of failure of a component is shown below:

Table 3-2: Ranking scheme for consequence ratings

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description (expected cost of the consequence of failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>Failure has a knock on effect on the entire operation thus causing massive production loss apart from rectification costs. Heavy-duty crane ships are needed for rectification.</td>
</tr>
<tr>
<td>High</td>
<td>Failure results in a stand-alone loss of production apart from rectification costs. Heavy-duty crane ships may be needed for rectification.</td>
</tr>
<tr>
<td>Medium</td>
<td>Failure results in production loss; damage is rectified using lighter crane ships</td>
</tr>
<tr>
<td>Low</td>
<td>Failure results in partial production loss; damage may be rectified using lighter equipment ship</td>
</tr>
<tr>
<td>Very low</td>
<td>Failure results in a very temporary production loss; damage is rectified by using light equipment</td>
</tr>
</tbody>
</table>
Table 3-3: Qualitative risk ranking

<table>
<thead>
<tr>
<th>Component</th>
<th>Likelihood</th>
<th>Consequence</th>
<th>Risk Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elec Control</td>
<td>High</td>
<td>Medium</td>
<td>48</td>
</tr>
<tr>
<td>Gear Box</td>
<td>Low</td>
<td>Very High</td>
<td>40</td>
</tr>
<tr>
<td>Yaw System</td>
<td>Low</td>
<td>Medium</td>
<td>24</td>
</tr>
<tr>
<td>Entire Turbine</td>
<td>Low</td>
<td>Very High</td>
<td>40</td>
</tr>
<tr>
<td>Generator</td>
<td>Medium</td>
<td>High</td>
<td>48</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>Low</td>
<td>High</td>
<td>32</td>
</tr>
<tr>
<td>Grid Connection</td>
<td>Medium</td>
<td>Low</td>
<td>24</td>
</tr>
<tr>
<td>Blades</td>
<td>Medium</td>
<td>Medium</td>
<td>36</td>
</tr>
<tr>
<td>Brakes</td>
<td>High</td>
<td>Medium</td>
<td>48</td>
</tr>
<tr>
<td>Axle/ Bearing</td>
<td>Medium</td>
<td>Medium</td>
<td>36</td>
</tr>
<tr>
<td>Mech Control</td>
<td>High</td>
<td>Medium</td>
<td>48</td>
</tr>
<tr>
<td>Entire Nacelle</td>
<td>Medium</td>
<td>Medium</td>
<td>36</td>
</tr>
<tr>
<td>Coupling</td>
<td>Medium</td>
<td>Medium</td>
<td>36</td>
</tr>
<tr>
<td>Tower collapse</td>
<td>Medium</td>
<td>High</td>
<td>48</td>
</tr>
<tr>
<td>Foundation</td>
<td>Low</td>
<td>Very High</td>
<td>40</td>
</tr>
</tbody>
</table>

For simpler systems it is possible to plot the risk on a risk matrix (discussed in Appendix F) in terms of the items assigned likelihood and consequence ratings as shown in the second and third columns of table 3-3. Usually systems are more complex and additional steps are required to assess risk. The next step imparts more discrimination to the risk assessment procedure used for complex systems such as wind turbines.

The product of normalised numerical values for likelihood and consequence of failure gives a risk priority measure (RPM) or a risk score. This is shown in table 3-3, 4th Column.
RPM = (Normalised value of likelihood of failure) x (Normalised value of consequence of failure)

The process of normalization is as follows:

If VL, L, M, H and VH can be represented by 20, 40, 60, 80 and 100, then the risk profile of an item, say the yaw system in table 3-3 above, which is ranked Low (40) on likelihood and Medium (60) on the consequence of failure, can be represented as

\[(40 \times 60)/100 = 24,\]

where 24 is the RPM of the yaw system. It must be noted here that these values are relative values.

A histogram uses the RPMs to prioritize components in terms of their risk and thereby highlight those components that need more attention, see figure 3-1.

![Risk Histogram using Risk Priority Measure (RPM)](image)

As shown in the figure, the collapse of the tower is in itself not a frequent event, but the risk (RPM value 48) from such an event arises from the severity of the consequence. The blades of a wind turbine have a high likelihood of being damaged, but the consequence severity is not so high and hence the risk of such an event is less than that from a collapse of tower. (RPM
value 36). The values here are for demonstration only. In certain areas, for example in the vicinity of human inhabitation or plant and machinery, the risk to life/property posed by pieces of damaged blade flying off may be considerable.

3.2 QUANTITATIVE ANALYSIS OF WIND TURBINE TOWER

3.2.1 CONCEPT

As seen in the previous section, a qualitative risk assessment helps maintenance personnel to focus on high-risk components for further action. The next stage is to, as far as is practicable, conduct a quantitative risk analysis of the component(s) identified as being high risk. Quantitative analysis raises the decision making tool to a higher level of precision and risk discrimination.

Quantitative analysis replaces the qualitatively assessed VL-VH failure likelihood and consequence estimates with a numerical failure probability and a numerical consequence value, usually represented by cost (£, $ etc.). For example, if the failure probability of a structure is 0.05 per year and the consequence cost of such a failure is £100,000, then risk in quantitative terms is the expected consequence cost should the failure of the structure occur,

\[
\text{Risk (\£/year)} = (\text{Probability of Failure}) \times (\text{Consequence cost of the failure})
\]

\[
= (0.05) \times (100,000)
\]

\[
= 5000.
\]
It must be noted that although not explicitly mentioned here or elsewhere, the failure probability considered above and in the wider context of this thesis is, in fact, a joint probability. It is, in effect, not just the probability of failure but the probability of a failure leading to the specific consequence in consideration. For example, consider a container containing an inflammable fluid being assessed. Assume that there is only one type of failure i.e. ‘Loss of containment’ leading to only two possible consequences- ‘No fire’ and ‘Fire’- as shown in figure 3-2. Then,

\[ \text{Probability of fire} = (\text{The probability of failure}) \times (\text{The probability of ignition}) \]  \hspace{1cm} (3.1)

Here, the probability of fire is a joint probability and not just the probability of failure. In the discussion here, unless indicated otherwise, the probabilities are probabilities of failure leading to the specific consequence under consideration.

A quantitative analysis could have deterministic values, a range of values or a distribution to reflect the underlying uncertainty as input. A stochastic process is a process with an
indeterminate or random element as opposed to a deterministic process that has no random element. In a stochastic process, inputs and/or outputs are a distribution of values described by a probability function. For example, corrosion rate in a deterministic model may be 0.3 mm/year, whereas in stochastic model would be, say, a normal distribution, $N(0.3, 0.05)$ with mean 0.3 mm/year and a standard deviation of 0.05 mm/year. Most damage mechanisms are stochastic in practice and need to be evaluated as such.

### 3.2.2 Probabilistic Remaining Life Methodology

Failure probabilities are difficult to ascertain. There are a number of methods to obtain failure probability versus time data:

a) Using specific failure information: One method is to use specific failure data that is plant, equipment or component specific, and is gathered from local sources such as maintenance and inspection histories. This is usually the best source of information because it is specific to local operating conditions such as weather, management strategy etc. However, such failure data may not be available, or if available, may not be statistically significant. Specific failure information can also be generated from industry experts.

b) Using generic failure data: This data is obtained from original equipment manufacturers (OEMs), industry experts or public sources. In a way, it is a collection of specific information. Although such a data set represents a range of operating conditions across a larger population of equipment, it is an excellent point of reference. The data is statistically more significant as it is taken from a bigger population of equipment across industries. Such databases exist in the Oil & Gas, power generation and aviation industries.
c) Conducting engineering analysis: There are methods for predicting damage rates and these can be incorporated in probabilistic models to calculate probabilities of failure.

The procedure here considers engineering analysis to demonstrate the technique of using quantitative analysis as input to a risk model. A measurable degradation mechanism—corrosion—has been chosen for which a probabilistic degradation model has been created. A typical asset remaining life (RL) calculation has statistical distributions describing the damage rate, the materials properties and the current damage state. These distributions are inputs to the life calculation. In the technique described here, by using Monte Carlo Simulation (MCS) software, random values are selected from each input distribution. The calculation is repeated many times selecting random combinations of values from all inputs. Instances in which RL is negative are counted as failure to calculate the probability of failure. The sections that follow discuss the RL model further.

A failure modes and effects analysis identified corrosion, fatigue and scouring as the significant degradation mechanisms affecting WT towers. The rate and action of these degradation mechanisms can be quantified in terms of a probabilised damage model and loading environment based on some assumptions. This quantitative assessment of failure probability can then be used as input into a model for optimising inspection and maintenance.

In this work a risk model has been developed for corrosion but similar models could be developed for fatigue and scouring. A full analysis would take all these mechanisms into account. However, this work serves to illustrate the general approach.


3.2.3 DEGRADATION MECHANISMS

From the failure modes and effects analysis the following mechanisms causing degradation to a WT tower structure were identified and are now discussed.

(a) Fatigue

The tower structure of a wind turbine is subjected to cyclic stresses causing fatigue. These stresses originate from sources including variations in the wind loading, the effects of waves and vibration induced by the movement of the turbine itself. The cyclic stresses cannot be easily calculated since the loads are not well defined, but an alternative is to measure the strain, or better still the fatigue damage, directly using strain gauges or a fatigue sensor system.

There are a number of fatigue sensor systems in the market to assess fatigue in welded joints, which are the areas most susceptible to fatigue. One such sensor- CrackFirst™ - developed in a project funded by the DTI’s LINK Sensor and Sensor Systems for Industrial Applications Programme is briefly discussed here. (More information is available at http://www.strainstall.com/.)

The fatigue sensor is installed on a welded steel structure. It indicates the portion of fatigue design life of the structure consumed. The sensors are so placed that they are subjected to the same loading history as the structure they are monitoring. They record the cumulative fatigue damage of the structure and thus enable engineers to estimate its remaining life.

There are several ways of powering and interrogating the sensor. For remote locations, such as offshore wind farms, an on-board electronics unit that checks the sensor status and records
the same for download to a Bluetooth enabled PC (range of about 10 meters), can be used. Data in the following format (table 3-4) can be obtained from such a sensor:

**Table 3-4: Fatigue sensor output**

<table>
<thead>
<tr>
<th>Reading (year)</th>
<th>Fatigue design life consumed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>28</td>
</tr>
</tbody>
</table>

Estimates of the fatigue design life consumed at several points in the structure may be used in the sort of risk model for the failure of the structure as a whole, as described below. The probability of failure by fatigue increases with the amount of fatigue design life consumed. The output of the sensor can thus be used to estimate the probability of failure for the tower as a whole.
(b) Scouring

Scouring results from the erosion of soil particles at or near the tower foundation caused by waves or currents. Scouring may affect the ultimate and fatigue load capacity of the tower structure. Equations to predict scouring and means of preventing scouring are given in the DNV Offshore Standard on Wind turbines (Det Norske Veritas June 2004). Again, the variations or uncertainties in the depth of scouring and the loading can be translated into a probability of failure by engineering analysis, but this was beyond the scope of this work.

(c) Corrosion

FMEA highlighted corrosion as one of the main damage mechanisms affecting the integrity of the structure of a wind turbine tower. There is no fixed value that is universally accepted for the corrosion rate of steel in ambient temperature sea water. Although corrosion rates are often treated as constant over time, some experts believe that the corrosion rate of steel in sea water decreases with time.

The probabilistic model discussed in the next section assumes a hypothetical distribution for the corrosion rate. In practice, this distribution may be obtained by fitting a curve to the corrosion values obtained from historical data from similar structures operating in a similar environment.

Failure modes and effects analysis to identify consequences of damage to a wind turbine tower:

The analysis here considers consequences to be business critical rather than safety critical. Hence, the cost of consequence will include repair or replacement costs and lost revenue.
during downtime, all of which are relatively easy to quantify, see table 3-5. The table is the result of a dedicated brainstorming session at TWI Ltd.

### 3.2.4 QUANTITATIVE CONSEQUENCE ANALYSIS

Table 3-2 shows a ranking scheme for consequence ratings. A more comprehensive one with more quantitative assessment using FMEA is shown in table 3-5. The table is for illustration only. There may be some intangibles remaining or if quantified, may be approximate assessments; for example, ‘technology confidence loss’ may be quantified in some way—losing similar projects or a drop in the share value of the company.

In the analysis that follows, for simplicity, the consequence considered and quantified is just the production loss.

### 3.2.5 QUANTITATIVE PROBABILISTIC DAMAGE MECHANISM MODEL FOR FAILURE DUE TO CORROSION

This thesis does not discuss the details of damage models for use in probabilistic analysis. Instead it illustrates a simple probabilistic damage mechanism model for general corrosion of the tower structure. Consider a structure subject to corrosion. For the sake of simplicity, assume that this is the only damage mechanism causing failure of the structure and that there is a breakdown of coating. The remaining life (RL) of the structure can be calculated as:
\[ RL = \frac{(T_c - MAT)}{CR} \]  

(3.2)

Table 3-5: Identified consequences and associated costs of damage to a wind turbine tower

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Effect</th>
<th>Consequence category</th>
<th>Consequence</th>
<th>Cost (£k)</th>
<th>Source/comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion - Uniform Band in Splash Zone</td>
<td>Collapse</td>
<td>Production loss</td>
<td>Maintenance duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrosion - Uniform Band in Splash Zone</td>
<td>Collapse</td>
<td>Secondary Damage</td>
<td>Other turbines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrosion - Uniform Band in Splash Zone</td>
<td>Collapse</td>
<td>Personel</td>
<td>Injury</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrosion - Uniform Band in Splash Zone</td>
<td>Collapse</td>
<td>Maintenance costs</td>
<td>Installation of new structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrosion - Uniform Band in Splash Zone</td>
<td>Collapse</td>
<td>Reputation</td>
<td>Insurance premium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrosion - Uniform Band in Splash Zone</td>
<td>Collapse</td>
<td>Find and Assess</td>
<td>Repair</td>
<td>Maintenance cost</td>
<td></td>
</tr>
<tr>
<td>Fatigue - Circumferential cracking</td>
<td>Collapse</td>
<td>Production loss</td>
<td>Maintenance duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue - Circumferential cracking</td>
<td>Collapse</td>
<td>Secondary Damage</td>
<td>Other turbines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue - Circumferential cracking</td>
<td>Collapse</td>
<td>Personel</td>
<td>Injury</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue - Circumferential cracking</td>
<td>Collapse</td>
<td>Maintenance costs</td>
<td>Installation of new structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue - Circumferential cracking</td>
<td>Collapse</td>
<td>Reputation</td>
<td>Insurance premium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue - Circumferential cracking</td>
<td>Collapse</td>
<td>Find and Assess</td>
<td>Repair</td>
<td>Lost production</td>
<td></td>
</tr>
<tr>
<td>Fatigue - Circumferential cracking</td>
<td>Collapse</td>
<td>Keep in service</td>
<td>Maintenance cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scouring</td>
<td>Collapse</td>
<td>Production loss</td>
<td>Maintenance duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scouring</td>
<td>Collapse</td>
<td>Secondary Damage</td>
<td>Other turbines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scouring</td>
<td>Collapse</td>
<td>Personel</td>
<td>Injury</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scouring</td>
<td>Collapse</td>
<td>Maintenance costs</td>
<td>Installation of new structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scouring</td>
<td>Collapse</td>
<td>Reputation</td>
<td>Insurance premium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scouring</td>
<td>Collapse</td>
<td>Find and Assess</td>
<td>Repair</td>
<td>Lost production</td>
<td></td>
</tr>
<tr>
<td>Scouring</td>
<td>Collapse</td>
<td>Keep in service</td>
<td>Maintenance cost</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where, \( RL \) = remaining life (years); \( T_c \) = current thickness of the structure (mm);

\( MAT \) = minimum allowable thickness to maintain integrity of the structure (mm); and

\( CR \) = corrosion rate (mm/year). These terms are explained in more detail later in this section.

If \( T_o \) is the original nominal thickness of the structure, then at the end of \( t \) years,
\[ T_c = T_o - CR \times t. \quad (3.3) \]

The reliability of an element of a system can be determined based on a performance function that can be expressed in terms of basic random variables \( X_i \) for relevant random loads and structural strength (Ayyub, 2003).

Mathematically, the performance function \( Z \) can be described as

\[ Z = (X_1, X_2, ..., X_n) = R - L \quad (3.4) \]

where, \( R \) is the resistance or strength and \( L \) is the load.

The limit state can be defined as

\[ Z = 0. \quad (3.5) \]

Accordingly, when \( Z < 0 \), the element is in the failure state, and, when \( Z > 0 \), it is in the survival state.

The limit state equation implied in equation (3.2), when remaining life is zero, can be expressed as

\[ RL = \frac{(T_c - MAT)}{CR} = \frac{(T_o - CR \times t - MAT)}{CR} = 0, \quad (3.6) \]

\[ T_o - CR \times t - MAT = 0, \] which can be re-arranged to

\[ [T_o - MAT] - [CR \times t] = 0. \quad (3.7) \]

where, the first term represents structural strength \( R \), and the second, load effect \( L \).

A purely deterministic RL model would have each independent variable in equation 3.2 as a specific value. This assumes that these variables have no random or probabilistic aspects but can be defined in a fixed predictable fashion. In reality, there is considerable
uncertainty associated with these variables and each can be defined by a statistical
distribution of values.

The corrosion rate (CR) maybe derived from periodic in-service measurements of metal
loss resulting from corrosion or from laboratory tests. In the calculations that follow, CR is
assumed to be a normal distribution with a mean of 0.4mm/year and a standard deviation
of 0.1mm/year, N (0.4, 0.1). These values are for demonstration only. As CR cannot be
negative, the distribution is truncated to so that the lower boundary is greater than or equal
to zero.

The RL model has been created using the ‘@Risk’ software from Palisade Corporation.
Figure 3-3 depicts the distribution for CR using the @Risk software. Numbers on the
horizontal axis represent the corrosion rate in mm/year. (The percentage values on the
horizontal axis show what percentage lie in a given range of values- this is not used in the
below. The values on the vertical axis in figure 3-3 are also not used in the calculation
below.) The distribution can also be obtained from fitting a curve to real values of CR as
measured over a period of time and could well be a different kind of distribution.

![Figure 3-3: Corrosion rate (mm/year) distribution](image-url)
Current thickness ($T_c$) is known from the most recent thickness measurements on the structure, say during the year of assessment. If recent thickness measurements are not available, $T_c$ can be assumed to be equal to the original nominal thickness of the structure ($T_o$) as specified by the designer including tolerances, corrosion allowance, etc, and the RL calculated from the year of installation. For the purpose of demonstration, in the model, $T_o$ is also a normal distribution, $N(100, 1)$ i.e. with mean=100mm and standard deviation=1mm.

MAT is the absolute minimum allowable thickness calculated by the designer to prevent failure by overload, collapse, etc as appropriate. In the illustration this value is 90 mm. ‘Failure’ in this context is not having the minimum allowable design thickness (MAT) rather than actual physical collapse of the structure. The probability of not meeting MAT is greater than that of structural collapse as there is a factor of safety within the minimum design thickness, making the analysis conservative.

In the method here, the statistical analysis tool - Palisade’s @RISK for Microsoft Excel- is used to describe all the independent variables probabilistically, and RL is then calculated using Monte Carlo Simulation (MCS) technique. In this way, the calculated RL by MCS is actually a distribution of values, so that the annual probability of failure (the failure rate per year) over time can be obtained. This annual probability of failure, in the current context, is effectively the proportion of surviving population of structures from the previous year that is expected to fail within the year under consideration.

Annual probability of failure = $P(RL \leq 0)$ \hspace{1cm} (3.4)

For example, see figure 3-4 that shows an assessment of the annual probability of failure of a tower structure with (1) an initial (in the year of installation i.e. 2000) thickness of 100 mm with some deviation described by $N(100,1)$; (2) Expected CR as $N(0.4, 0.1)$ with
negative values truncated; (3) MAT as 90 mm. The number of iterations is set to 1000. This means that for year 2000, 1000 values for CR and Tstart are selected from the respective stipulated distributions. These initial values are used in calculations for the year 2000 and all the subsequent years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Tstart</th>
<th>CR</th>
<th>Tend</th>
<th>PoF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>%</td>
</tr>
<tr>
<td>2000</td>
<td>100.0</td>
<td>0.4</td>
<td>99.6</td>
<td>0.0</td>
</tr>
<tr>
<td>2001</td>
<td>99.6</td>
<td>0.4</td>
<td>99.2</td>
<td>0.0</td>
</tr>
<tr>
<td>2002</td>
<td>99.2</td>
<td>0.4</td>
<td>99.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2003</td>
<td>98.8</td>
<td>0.4</td>
<td>98.4</td>
<td>0.0</td>
</tr>
<tr>
<td>2004</td>
<td>98.4</td>
<td>0.4</td>
<td>98.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2005</td>
<td>98.0</td>
<td>0.4</td>
<td>97.6</td>
<td>0.0</td>
</tr>
<tr>
<td>2006</td>
<td>97.6</td>
<td>0.4</td>
<td>97.2</td>
<td>0.0</td>
</tr>
<tr>
<td>2007</td>
<td>97.2</td>
<td>0.4</td>
<td>96.8</td>
<td>0.0</td>
</tr>
<tr>
<td>2008</td>
<td>96.8</td>
<td>0.4</td>
<td>96.4</td>
<td>0.0</td>
</tr>
<tr>
<td>2009</td>
<td>96.4</td>
<td>0.4</td>
<td>95.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2010</td>
<td>96.0</td>
<td>0.4</td>
<td>95.6</td>
<td>0.0</td>
</tr>
<tr>
<td>2011</td>
<td>95.6</td>
<td>0.4</td>
<td>95.2</td>
<td>0.0</td>
</tr>
<tr>
<td>2012</td>
<td>95.2</td>
<td>0.4</td>
<td>94.8</td>
<td>0.1</td>
</tr>
<tr>
<td>2013</td>
<td>94.8</td>
<td>0.4</td>
<td>94.4</td>
<td>0.7</td>
</tr>
<tr>
<td>2014</td>
<td>94.4</td>
<td>0.4</td>
<td>94.0</td>
<td>1.1</td>
</tr>
<tr>
<td>2015</td>
<td>94.0</td>
<td>0.4</td>
<td>93.6</td>
<td>2.2</td>
</tr>
<tr>
<td>2016</td>
<td>93.6</td>
<td>0.4</td>
<td>93.2</td>
<td>5.8</td>
</tr>
<tr>
<td>2017</td>
<td>93.2</td>
<td>0.4</td>
<td>92.8</td>
<td>8.4</td>
</tr>
<tr>
<td>2018</td>
<td>92.8</td>
<td>0.4</td>
<td>92.4</td>
<td>13.3</td>
</tr>
<tr>
<td>2019</td>
<td>92.4</td>
<td>0.4</td>
<td>92.0</td>
<td>19.4</td>
</tr>
<tr>
<td>2020</td>
<td>92.0</td>
<td>0.4</td>
<td>91.6</td>
<td>25.5</td>
</tr>
<tr>
<td>2021</td>
<td>91.6</td>
<td>0.4</td>
<td>91.2</td>
<td>30.2</td>
</tr>
<tr>
<td>2022</td>
<td>91.2</td>
<td>0.4</td>
<td>90.8</td>
<td>36.1</td>
</tr>
<tr>
<td>2023</td>
<td>90.8</td>
<td>0.4</td>
<td>90.4</td>
<td>43.3</td>
</tr>
<tr>
<td>2024</td>
<td>90.4</td>
<td>0.4</td>
<td>90.0</td>
<td>50.7</td>
</tr>
<tr>
<td>2025</td>
<td>90.0</td>
<td>0.4</td>
<td>89.6</td>
<td>68.3</td>
</tr>
<tr>
<td>2026</td>
<td>89.6</td>
<td>0.4</td>
<td>89.2</td>
<td>61.5</td>
</tr>
</tbody>
</table>

**Figure 3-4: Screenshot of inputs and outputs of the corrosion model**

For every year, equation 3.2 is used to calculate the annual probability of failures. For example, in the year 2013,

\[ T_{start} = 94.8 = T_c \]

where 94.8 in effect represents the mean of 1000 iterations;

\[ T_c - MAT \] too has 1000 values.
The algorithm counts the number of times $Tc - MAT$ is negative or zero; in this case 7 times out of a total of 1000 iterations. These are the times when, as per equation 3.2, $RL \leq 0$. Percentage values give $P(RL \leq 0)$ as shown in column 5 in figure 3-3.

This annual probability of failure (failure rate) versus time curve is used in the next stage in which the timing of an action (repair/ replacement) can be optimised such that financial benefit is optimised.

![Annual probability of failure (PoF) Vs time](image)

Figure 3-5: The annual probability of failure versus time curve

3.3 RISK BASED FINANCIAL OPTIMISATION OF MAINTENANCE ACTION GIVEN A FAILURE TREND

3.3.1 THE NEED FOR FINANCIAL CRITERION IN MAINTENANCE DECISION MAKING

Maintenance projects are increasingly being evaluated by decision makers who need to understand the implications of various options in financial terms. Although predictive maintenance techniques have matured, the predictions are in engineering terms. Thus, there
is a need to express the effects of engineering wear and tear in financial terms. In the current context, this is done by evaluating the cost of the consequences of failure owing to wear and tear of plant and machinery.

### 3.3.2 The Drivers for a Consistent Decision Making Methodology in Maintenance

Many old plants, structures, capital equipment or components are in their Ageing period of life. However, increasing competition means many of them cannot be replaced and need to have their useful life extended. In addition, new components are often designed to operate with maximum efficiency, and are designed with lower “margins of error” against assumed operating conditions.

Each action (or project) has costs associated with it. These costs are, in essence, investments made by the concerned asset owner with the expectation of certain return on the investment(s). The decision maker will normally be faced with a number of projects competing for such investments, and therefore needs to take decisions that maximise the returns on these investments. The most widely understood financial techniques to evaluate projects include ‘return on investment’, ‘pay-back period’ and ‘discounted cash flow (DCC)’ methods (Brealey, Myers 1991). These techniques have various strengths and weaknesses. The methodology here employs the net present value (NPV) technique that is a form of DCC analysis

### 3.3.3 NPV in Financial Analysis

In the current discussion, it is assumed that a project with a higher NPV is a better investment than a project with a lower NPV. The NPV of a project is the present (current)
value of the total future cash flows, i.e. the net of both positive (income) and negative (cost) cash flows. NPV considers the time value of money by discounting all the cash flows, and it is calculated as follows:

\[
NPV = \sum_{t=0}^{N} \frac{(C_t)}{(1 + r)^t}
\]  

(3.5)

N = project life (years); t = timing of cash flow (year); r = interest rate, or discount rate; and Ct = cash flow in year t.

The future cash flows are ‘expected’ cash flows, as they do not occur with certainty. The uncertainty arises in the engineering analysis to calculate the probability of failure over time for the damage mechanism(s) of interest.

The risk associated with any project is expressed in terms of its NPV by using expected values (EV). The EV of a failure event is the product of the probability of an event occurring and the cost of consequence of that event. The probability of an event and the cost of the consequence(s) of that event is directly assessed from prior quantitative analyses; the consequence cost is expressed in financial terms.

Thus, the NPV of a project with uncertain outcomes is the sum of the expected values of all future discounted cash flows, as follows:

\[
NPV = \sum_{t=0}^{N} \left( p_t \times C_t \right) \div (1 + r)^t
\]

(3.6)

where, \( p_t \) = the probability of the event occurring at time t.
3.3.4 THE RISK-BASED OPTIMISATION MODEL

The optimisation maximises the NPV of the action (repair/replacement) under consideration. In this case, the optimisation finds the least negative value of NPV. Cash inflows are treated as positive and cash outflows as negative: 1) money spent on an action is negative, 2) failure consequence costs ((unplanned) outages due to failure- mainly production loss considered here, for simplicity) is also negative, but 3) failure costs avoided by undertaking the action under consideration are considered positive.

Consider that our planning period is from t=0 to t=N and the year of assessment is t=0. Let us consider the NPV of an action undertaken in any year t=n. It is given by:

\[
\text{NPV} = (\text{Expected present value of action undertaken in year } t=n) + (\text{Expected present value of costs due to outages prior to the action}) + (\text{Expected present value of costs due to outages avoided due the action})
\]

\[
(3.7)
\]

The first two terms in equation 3.11 are negative, the third is positive.

Hence,

\[
\text{NPV} = \left\{- \left[ \sum_{t=n}^{t=N} \left(C_{Bt} \times (1 + r)^{t-n} \right) \right] + \left[ - \left[ \sum_{t=0}^{t=n} (C_{Pt} \times C_{Bt}) \times (1 + r)^{t-n} \right] \right] \right\} + \left\{ \sum_{t=n+1}^{t=0} \left( \sum_{t=0}^{t=N} (C_{Pt} \times C_{Bt}) \times (1 + r)^{t-n} \right) \right\}
\]

(3.8)

In equation (3.12), for the NPV of an action taken at time t=n, the following can be defined:

\[
C_{Bt} = \text{Cash flows associated with production in year } t;
\]

\[
C_{Pt} = \text{Cash flows associated with implementing the project in year } t, \text{ including any tax credits (positive cash flow) on depreciation costs (Collier, Glagola 1998)};
\]

\[
N = \text{the maintenance planner’s strategic planning period, i.e. from } t=0 \text{ to } t=N;
\]

\[
n = \text{year in which the action is proposed to be undertaken};
\]
pt = probability of the event (failure leading to the particular consequence) occurring in year ‘t’; and

r = interest rate, i.e. the cost of money (finance).

The optimisation algorithm calculates the year of maintenance action for which the NPV is maximum (least negative, in this case), subject to stipulated constraints.

The maintenance action may be replacement or repair. In both cases, it is assumed that the cost of action includes the cost of initial problems (teething problems) and that once the equipment or structure is in place and functional, it begins its life cycle at a relatively very low failure rate.

The key inputs to the optimisation model are as follows:

(a) The annual probability of failure versus time values using which expected values are derived as per the formula discussed above; the failure trend is obtained from quantitative assessments.

(b) The consequence cost of failure (unplanned outage).

(c) Interest rates and depreciation as applicable.

(d) Any financial constraints, such as the annual maintenance budget limit.

(e) Although not shown in the calculations here, any non-financial constraints, e.g. those on failure rates due to safety regulations.

3.3.5 DEMONSTRATION OF THE MODEL

The approach described above is demonstrated by evaluating three offshore wind turbine tower structures. The failure trend from a probabilistic corrosion model is presented in
figures 3-4 (spreadsheet calculations) and 3-5 (graphical presentation). How the Action NPV (depicted by the curve with triangles) changes with the failure trend (curve with square boxes; the same curve as shown in figure 3-5) is shown figure 3-6. The values are obtained using equation 3.7 for each year in the planning period.

![The NPV of an action to mitigate the probability of failure over the operating life of a structure/equipment](image)

The optimised replacement time for Structure 1- year 2016- is shown in figure 3-6. This is the year in which the ‘Action NPV’ is the least negative.

The figure depicts the application of risk based approach to undertaking run-repair-replace decision-making for structure 1. The probability of failure versus time curve derived from remaining life estimates on its own is often incomplete information to the decision maker. The Action NPV versus time curve generated by the risk based approach enables one to make a more informed maintenance decision by considering the consequences of failure.
too. Thus the context in which the structure is operating and the implications of it failing feed into the process of run-repair-replace decision-making.

The optimised action years for the other two structures are derived in the same way. This is shown in figure 3-7. It is seen that both structure 1 and structure 2 have the same year of replacement- 2016, and structure 3 has 2012 as the year of replacement. The figure shows a scenario in which the budget for repair/ replacement of structures in a wind farm is set to maximum of £ 6400,000 in any given year with an increase of 0.05 % every year. It is assumed that if this budget is not used in a given year on asset management actions within this wind farm, it is used elsewhere- there is no facility for a rollover. Due to this limit on expenses, if actions are taken as calculated, there would be deficits in the years in which the actions are taken.

To address this, optimisation is carried out again (using Solver in Microsoft Excel). The rescheduled time of action is shown in figure 3-7. All actions are now within the allocated budget. However, the change in schedule comes at a price: the NPV decreases from the previously optimised value of - £ 7118677 to -£ 7148132. To take the analyses one step further this loss in NPV could be compared to the expected cost of borrowing to see if actions can be taken in the years as originally identified as the most optimum time.
Figure 3-7: Optimised action schedule leading to budget deficit arising due to two structures being replaced in the same year (2016)
Figure 3-8: Re-scheduling the year of action such that the costs lie within allocated budget
3.3.6 IN-SERVICE INSPECTION OPTIMISATION

The model could be extended to inspection actions. Instead of the replacement cost of the component, the cost of in-service inspection would be considered. Since such actions (projects) are usually accounted for as ‘expenses’ in the year in which they occur, rather than as ‘investments’ (which would then be written-off over several years), tax credits from depreciated costs do not arise. Since inspection costs are relatively low compared to production loss it is expected that the model would suggest the optimum year of inspection to be the first year of the planning period. To address this, ASME (ASME 2003a) suggest the following course of action to optimise in-service inspection dates:

1. Optimise the action date as if the action was replacement,
2. Inspect the equipment before this calculated replacement date,
3. Compare the actual component damage found during inspection, to the projected conditions, and then
4. Replace the component if necessary, or re-calculate a new optimised replacement date.

3.3.7 DISCUSSION

In the RBLM optimisation model presented above, the following points warrant further discussion:

(1) Multi-component optimisation

It has been shown that the optimum year of replacement can be calculated when the net present value (NPV) of the maintenance action is maximised. If in a system of structures
there is a budgetary constraint that does not allow for a series of actions to be undertaken in a given strategic planning period, further optimisation can be undertaken using the approach.

(2) Quantitative inputs

The technique requires a quantitative assessment of degradation/damage. This is at times expensive, time consuming and requiring simplifying assumptions to be made.

As in all models, the outcome is sensitive to the variation in the inputs. This is all the more true in complex models in which inputs are not fixed and may be in the form of distributions. Volatility in the inputs may manifest in higher volatility and uncertainty in the outcome. Such levels of uncertainty may limit the applicability of such models.

(3) RBLM models in complex systems

For more complex systems with increasing number of components and constraints, non-linear optimisation tools (e.g. those based on genetic algorithms) that are more powerful than the linear Solver in Microsoft Excel may be required.

(4) Direction of future relevant work

There is scope for further work on deriving failure estimates using expert elicitation and combining failure probabilities using Bayesian methods to update prior probability distributions with other data sources, e.g. combining specific failure databases with expert knowledge. More research is needed in assessing the use of genetic algorithms for optimisation in complex systems. Finally, further work is needed to incorporate a wider range of in-service equipment damage mechanisms to optimise RBLM actions.

(5) The application of risk based approaches such as the one presented here does not require as a pre-requisite that failure data be in shape of the bath tub curve mentioned in
the previous chapter. Although it is often useful to assume that damage will accumulate over time and manifest itself in terms of an increasing failure rate, real operational data may not indicate this for a number of reasons shown in 2.3.2. Risk based approaches use a measure of risk to undertake asset integrity methods. The risk in a system of assets may vary during its operational life and not follow a fixed trend.

3.4 CONCLUSIONS FROM THE PROJECT

The project developed a RBLM methodology for the management of offshore wind farms. The risk-model developed for implementing the methodology finds the optimum time of an action - repair/replacement- of a component at risk of failure under the action of degradation mechanisms such that financial benefit is maximised.

To demonstrate the working of the model, a basic probabilistic model to obtain failure rates due to the action of an identified degradation mechanism- corrosion- has been developed. The focus in this chapter is on how to use this quantitative assessment of the probability of failure to undertake run-repair-replace decision-making such that the net present value (NPV) of such action is the maximum.

The RBLM approach demonstrated for wind turbine tower structures of offshore wind farms can be used in asset life management in other industry sectors as well.
4 PROJECT 2: RISK BASED OPTIMISATION OF SPARES INVENTORY MANAGEMENT

4.1 INTRODUCTION

4.1.1 THE CONTEXT

All businesses need to manage risks. Almost always there are competing risks and finite resources available to manage them. The research described here proposes an innovative methodology to minimize risks within a budgetary constraint, or to minimize the budget required to operate at specified acceptable levels of risk. In the current context, there is demand for spare parts that needs to be met within available resources; the risk is the cost of not meeting a demand and having to bear the consequential cost, and the budget is the allocated financial resource to manage this risk.

The research project presented here is in response to a real-life problem of developing a methodology for optimising the stocking of spare parts in the shipping sector. The research has benefitted from access to some databases used in spares management, and discussions with Shell International Trading and Shipping Company Limited (STASCO) and Lloyd’s Register (LR) regarding practical issues involved in the management of an inventory of spare parts.

The method is applicable to any business in which demand (in-house or external) for goods or services is required to be met, subject to some constraints. The constraints are mainly the funds available for meeting the demand and/or the maximum acceptable risk of not meeting
the demand i.e. having a stockout. A reasonable assumption is that some data - historical data or forecast indicating the demand in a given period - is available.

From the shipping industry where spares need to be stocked, to the hospitality sector where hotels need to order supplies, there is a requirement to prioritise the ordering within user specified constraints and often with limited demand forecast data. The model presented here provides an innovative risk based methodology to do the same.

4.1.2 THE APPROACH

The level of spares in an inventory has a direct bearing on machine availability. The availability of a machine is a function of the mean time to correct a failure which in turn depends upon, among other factors, the time to obtain a spare (to conduct repairs) or a replacement. The level of spares in a spares inventory is constrained by the cost of having stock and the penalty of being out of stock. In a competitive climate companies strive to keep their spares inventory at an optimum level to minimize the costs involved.

This research presents a new approach - a risk based approach - to spares inventory management aimed at establishing an optimum level of spares such that financial benefit is maximized within accepted levels of risk, and the remaining (residual) risks are clearly identified. The discussion here presents a framework that enables consistent and auditable decision making in spares inventory management.

Risk based approaches are used many sectors of industry and for prioritizing different types of actions; for example, there are risk based approaches in the process industry to manage maintenance and inspection and there are standards or guidance documents to implement these approaches (ASME International 2003b) (API Publication 2000) (API 2002a) (EEMUA 2006).
As opposed to other approaches, in a risk based approach, actions are based on the risk estimate of various options. In the current context, this means maintaining an inventory at an optimal level depending on the risk profile of the spares in which the likelihood of a failure to meet the demand for a spare is considered in conjunction with the consequences of the failure to meet that demand. The optimal level is such that financial benefits are optimised, given risk-associated constraints.

In the discussion below, some of the unique features of spares inventories vis-à-vis other types of inventories are mentioned at the outset. Then there is a section on typical costs associated with inventories followed by a brief note on the main principles underlying various current approaches to spares inventory management. The main body of the paper then presents the risk based methodology and the basic model that has been created to implement that methodology. This is followed by possible areas of further research and conclusions.

This chapter draws on two technical papers that were presented at different stages of relevant research. These are referred to in the text and attached in Appendices mentioned below:

Appendix B: "A risk based approach to spare parts inventory management", International Mechanical Engineering Congress and Exposition (IMECE) ASME, 2-6 November 2008, Boston, USA.

Appendix C: "Optimisation of resources for managing competing risks", 10th International conference on Engineering Structural Integrity Assessment, 19-20 May 2009, Manchester, UK.

4.1.3 SPARE PARTS INVENTORIES

Spare parts inventories are maintenance inventories; they are used by maintenance personnel to keep machines available and exist to meet an internal (in-house) demand for spares. They
perform a different function compared to other inventories such as Work-in-progress (WIP) inventories and Finished Product Inventories. WIP inventories smooth out irregularities in production flow. These irregularities are caused by factors such as changes in product mix, equipment breakdowns, differences in production rates, between processes and material handling. Finished Product Inventories provide a buffer stock to protect against lead time demand, differences in quality levels, differences in machine production rates, labour troubles, scheduling problems, gap between capacity and demand and other well established production problems (Kennedy, Wayne Patterson & Fredendall 2002).

Characteristics of spare parts inventories: Spares Inventories are hugely influenced by maintenance policies rather than customer usages that dictate WIP or Finished Product Inventories. For scheduled maintenance, the demand for spares is relatively more predictable and it may be possible to order parts to arrive just in time for use and indeed not stock such parts at all. For unplanned maintenance, a lack of some stock often means that the consequences of not keeping some stock include production loss and the extra cost incurred in procuring parts at short notice.

There are other factors such as the amount of redundancy within a system, the availability of information from condition monitoring equipment, the inter-dependency of failure events, the possibility of demands being met by cannibalism and the effect of parts or machine obsolescence on the level of stock holding. There has also been research illustrating how other factors such as the organizational context of inventories, especially the responsibilities and authorities of the persons concerned, have a bearing on inventory management, (Zomerdijk, de Vries 2003).
4.1.4 Typical costs associated with inventories

Businesses like to avoid excess inventory as there are costs incurred in keeping stock. Some of these are:

(a) Ordering and setting up costs: These are fixed costs that do not depend on the size of the order. For example, ordering costs would include paperwork and billing associated with the order. For parts made in-house, ordering and set up costs would include the cost of labour, setting up and shutting down the associated machinery.

(b) Unit purchasing cost: This is the variable unit cost of a part or a component. If the part is manufactured in-house, it includes the variable labour cost, the overhead cost, and the raw material cost needed to produce a single unit. If this part is ordered from an external source, then the unit purchase cost must include the shipping cost.

(c) Holding or carrying cost: These are essentially the inventory costs expressed in monetary value per unit part per year. It includes storage cost, insurance cost, taxes on inventory, and cost due to the possibility of spoilage, theft, or obsolescence. However, usually the most significant of the holding cost is the opportunity cost incurred by tying up capital in inventory. The opportunity cost is the return the company would expect on an investment elsewhere rather than in stock-holding.

(d) Stockout costs: When a demand for a product or a part is not met on time, a stockout is said to have occurred. If it is acceptable for demands to be met at a later date, no matter how much later, it is said that demands may be back-ordered. If it is necessary for demands to be met on time, and if this is not achieved, then the scenario is a lost case one.

In the current context, risk is the combination of the probability of a stockout event and its consequential cost, where a stockout is a lost case scenario. Such a stockout may result in
production loss, having to procure spares at an additional cost (‘distress cost’), knock-on failures requiring more parts and/or resulting in more production loss, regulatory penalty and other consequences such as loss of goodwill. Usually it is more difficult to measure the cost of a stockout rather than the cost of ordering, purchasing or holding.

4.1.5 APPROACHES TO INVENTORY MANAGEMENT

There are different approaches to Inventory Management. Prasad, categorizes inventory models into two: Economic Order Quantity (EOQ) and Materials Requirement Planning (MRP) (Prasad 1993). Under these, he classifies about ninety inventory models. The basic model in an EOR method determines, subject to a number of assumptions, an ordering policy that minimizes the yearly sum of ordering cost, purchasing cost, and the holding cost of a part in the inventory. The basic model in an MRP based method considers the relationship between a component that is demanded and other associated (sub) components that also need to be available in order to fulfil that demand.

Winston classifies models as Deterministic EOQ Models, Probabilistic Models and other recent models such as MRP, Just-in-time (JIT) and Exchange Curves (Winston 1993). Of particular interest, within probabilistic models, is the ABC classification system devised by General Electric during the 1950s. Within this system, in its very basic form, items are stocked according to empirical studies that show that 5%-20% of all items stocked account for 55%-65% of sales; these items are classified as Type A. Similarly Type B and Type C are items that account for a decreasing percentage of sales and are accordingly allocated lower priority in stocking.

ABC classification system seems to be inspired by the Pareto principle that, in its original form, says that 20% of a quantity is responsible for 80% of some other quantity i.e. causes:effect = 20:80; for example, 20% of business clients may account for 80% of the sales.
Indeed, Pareto Analysis is a useful technique in decision making where many possible courses of action are competing for attention. Such an analysis can identify the most effective actions within available resources that give a total benefit as close to the maximum possible one. Pareto Analysis is a creative way of looking at causes of problems, but can exclude those that are initially small and may grow over time; thus, it must be used in conjunction with other analytical tools such as FMEA, ETA and FTA.

To turn ABC classification on its head there is “The Long Tail” concept put forward by Chris Anderson (Anderson 2006). The assertion here is that products that are low in demand or have low sales volume can collectively make up a market share that rivals or exceeds the relatively few bestsellers and blockbusters, given a large enough store (stock) and distribution channels; this concept is gaining attention in a changing world with, inter alia, a shift to internet shopping and an increase in the demand for customised products.

Nahmias looks specifically at repairable inventory systems and classifies existing models into three general classes: continuous review, periodic review and models based on cyclic queuing systems (Nahmias 1981).

The risk based approach presented here is unique in that it does not completely fall in any of these categories although it might have some elements of the approaches listed above.

### 4.1.6 RISK BASED APPROACH TO INVENTORY MANAGEMENT

In the current context, the following terms have a special meaning: Risk is the combination of the probability of a stockout event and its consequence, where a stockout is an event when a spare is not available on demand. Qualitative risk analysis broadly covers methods that use engineering judgment and experience as the basis for the analysis of probabilities and consequences. Failure Modes, Effects, and Criticality Analysis (FMECA) and Hazard and
Operability Studies (HAZOPs) are examples of qualitative risk analysis that become quantitative risk analysis when consequences and failure probability values are estimated.

Quantitative risk analysis a) identifies and delineates the combinations of events that, if they occur lead to an undesired event b) estimates the frequency of occurrence for each combination c) estimates the consequences. The approach shown here is a semi-quantitative approach that captures best estimates from experts as well as raw historical data. The risk of a stockout referred here is relative risk, i.e. the risk of a stockout of a component or equipment in relation to each other.

In the method described below, a risk profile of the spares is obtained by considering the likelihood of a failure to meet the demand for a spare in conjunction with the consequences of the failure to meet that demand. This risk profile is then used to find the optimal level of inventory such that financial benefit is maximized given an identified acceptable risk level.

### 4.2 RISK OPTIMISATION MODEL

#### 4.2.1 UNDERLYING CONCEPTS AND ASSUMPTIONS

The model presented here was developed to address a situation as follows. There is an inventory of spares to service a fleet of ships. There is demand for parts of different kinds to keep these ships available for service. There is cost involved in purchasing and holding these parts in the inventory, and a penalty (risk) in not meeting demands for spares (stockouts).

There is some historical data available - in the form of the previous demands for each part within the timeframe considered. The question then is, what is the optimum numbers of the different parts the inventory should stock under the constraints of budget and/or acceptable risk of stockout? The risk model was developed using the principles of linear programming.
The model has two parts: Part 1 establishes some baseline values, and Part 2 optimises values.

The implementation of the approach is shown by way of an example shown in figure 4-1.

**Figure 4-1: Minimise Total Risk Value (TRV) subject to given Total Stock Cost (TSC) constraint**
4.2.2 PART 1: OBTAINING BASELINE VALUES:

This part of the model aims at establishing baseline values for certain parameters for the purpose of optimising in the second part of the model. The model is shown in figure 4-1. In the inventory considered, there are 10 types of parts. The parameters with their descriptions are as follows:

- $i =$ unique number representing type of part;

- $n_{i(\text{ideal})} =$ the number of parts that a company would ideally like to hold if it had no financial constraints to meet any possible demand that might reasonably be considered. (Other factors that influence managing stock, such as warehouse space requirements, spoilage, obsolescence can be factored in the model as shown later); the number is based on any or a combination of historical demand data, expert opinion and manufacturer’s recommendations. There are guidelines/procedures for combining data from various sources using, for example, Bayesian inference (Clemen, Winkler 1999), (ASME 2003b).

- $D =$ the maximum demand within the timeframe the company expects to meet if it held stock without financial constraints.

- $\alpha_i =$ ratio of the number of part $i$ stocked, say, $n_j$, to the number the company would ideally like,$$
\frac{n_j}{n_{i(\text{ideal})}}
$$

- $\alpha_{i(\text{ref})} =$ baseline value of $\alpha_i$ for planning purpose

- $n_{i(\text{ref})} = \alpha_{i(\text{ref})} * n_{i(\text{ideal})} =$ baseline number of part $i$, rounded to the nearest integer

- $C_i =$ unit cost of part $i$
$$CoS_i = \text{consequence of a stockout for part } i \text{ (weighted value)}$$

$$P(x_i) = \text{probability of a stockout for part } i,$$

$$= 1 - \frac{n_{i(\text{ref})}}{n_{i(\text{ideal})}} \quad (4.1)$$

Where $$P(x_i) = P(n_{i(\text{ref})} < x_i \leq n_{i(\text{ideal})})$$

given that

a) $$n_{i(\text{ref})}$$ is the quantity in stock and

b) $$x_i$$ is the number of that part demanded during the timeframe such that $$x_i > n_{i(\text{ref})}$$,

c) $$n_{i(\text{ideal})}$$ is the ideal number of part $$i$$ in stock to meet maximum demand

d) the number of parts demanded follow a discrete uniform distribution.

The nature of distribution depends on what sort of data one has and what confidence one has in the available data. The uniform distribution is usually used when there is little or no available data. A uniform distribution assigns equal probability to all values between its maximum and minimum. Other distributions can also be used in the model created here.

$$RV_i = \text{Risk value associated with stockout of part } i = CoS_i \times P(x_i) \quad (4.2)$$

$$TSC = \text{Total cost of stock for all parts } n_{i(\text{ref})} = \sum n_{i(\text{ref})} \times C_i \quad (4.3)$$

$$TRV = \text{Total risk value associated with stockouts for all parts } n_{i(\text{ref})} = \sum RV_i \quad (4.4)$$

(In the figures showing snapshots of the model, $$TSC_b$$ and $$TRV_b$$ are used in Part 1 of the model; the suffix ‘b’ is used to indicate baseline values.)
In the model, qualitative estimates of CoS\textsubscript{i}, Very High, High, Medium, Low, Very Low have been assigned values of 100, 80, 60, 40 and 20 respectively. In a more advanced model, these values would be a weighted average of values obtained by considering a number of consequence or impact factors. One such possible scheme is described later and shown in the figure 4-5.

4.2.3 PART 2: OBTAINING OPTIMISED VALUES:

Part 2 of the model optimises the number of each part held in stock from the reference values selected in Part 1 subject to specified constraints using a linear programming tool. The optimised values contain the subscript ‘o’. For example, \( n_{io} \) is the optimised value of units of part \( i \) to be held in the inventory.

4.2.4 WORKING OF THE MODEL

At the outset, in Part 1 of the model, a suitable value for \( \alpha_{i(ref)} \) is assumed; in figure 4-1, this is 0.90. \( \alpha_{i(ref)} \) (shown in the highlighted box with a small circle towards its top right corner) is a fraction of the ideal number of parts (a wish list) that a manager of an inventory would like to hold given that there will be demands necessitated by failures requiring these parts. This starting assumption is necessary to find baseline values for Total Stock Cost (TSC) and the Total Risk Value (TRV) of the inventory, say, \( TSC_b \) and \( TRV_b \) respectively where,

\[
TSC_b = \sum n_{i(ref)} \times C_i \tag{4.5}
\]

\[
TRV_b = \sum RV_i \tag{4.6}
\]

This part of the model establishes the correspondence between three critical values (1) the reference stock level as denoted by the ratio \( \alpha_{i(ref)} \) , (2) the total cost of the stock as denoted
by $TSC_b$ (in monetary units) and (3) the unitless $TRV_b$ denoting a measure of risk associated with the inventory.

The initial value of $\alpha_{i(ref)} = 0.9$, can be changed at any stage to bring the $TSC_b$ to a feasible level, if not so already.

The values above are, in essence, baseline values that establish what is an acceptable level of overall risk and the associated cost of stock holding at that level. Part 1 of the model determines these baseline values as a starting point, and part 2 of the model carries out the linear optimisation. In the model demonstrated here, the Linear Programming (LP) is through the Solver add-in to Microsoft Excel.

### 4.2.5 Example Applications

The model has three modes of operation performing three distinct functions. These are:

**(A) Minimize Total Risk**

Figure 4.1 shows the results when Total Risk Value (TRV) is minimized subject to a given budget for the purchase of stock, i.e. (TSC). As seen, TRV reduces from 87 before optimisation to 16 after optimisation. Note that the portfolio of parts in the inventory has changed from the baseline or reference case. For example, for part 8 the initial reference holding of 9 has increased to 11, and instead of 9 of part 3, the optimised holding is only 2. Correspondingly, the RV of these parts has also changed.

**(B) Minimize Total Cost**

Figure 4-2 shows the results when budget for the purchase of stock (TSC) is minimized subject to maintaining the reference level of (assumed tolerable) Total Risk (TRV). As shown in the figure, the TSC comes down to £304,500 from £422,500, given a Total Risk Value
tolerance of 87. Again, the portfolio of parts in the inventory has changed from the baseline or reference case, but in a different way to that for minimising Total Risk above. Individual changes in the number of each part stocked and its contribution to Total Risk can be observed.

(C) Minimize Total Risk Value (TRV) or Total Stock Cost (TSC) subject to maximum individual risk constraints

Although optimisation has been carried out as described above, there may be some components for which the risk associated with a particular part may be considered too high to be acceptable to the decision maker. For example, as shown in figure 4-1, the optimised RV for part 3 i.e. \( RV_3 \) is 16; this is an expensive part of VL stockout consequence, but the likelihood value of a stockout relative to other parts is high at \( \beta_3 = 0.8 \). Similarly, in figure 4-2, Part 3 has a stockout likelihood of 1.00 (100%).

Such a high probabilities of stockout may be deemed too high by the decision maker especially when they are substantially different to that implied by \( \alpha_i(\text{ref}) \) that was assumed in part 1 of the model that established baseline values. It may be noted here that \( \alpha_i(\text{ref}) = 0.9 \) implies a reference stock level that plans to meet 90% of the maximum considered demand, i.e., 10% of maximum demand is expected not to be met resulting in a stockout probability of 10%. In these cases the decision maker would be likely to want to hold a greater number of these parts than the optimisation in modes A or B would suggest, even though the consequence of a stockout may be low.

To address the issue of having types of parts with a relatively very high probability of stockout, one more constraint is added to the above optimisation process. This is by way of adding a maximum acceptable stockout probability, \( P(n_{io})_{\text{max}} \) for each of the optimised
**Discussion**

**Part 1: Establishing baseline values**

<table>
<thead>
<tr>
<th>Part no.</th>
<th>Demand stock</th>
<th>Units in stock</th>
<th>Stock ratio</th>
<th>Unit cost</th>
<th>Total stock cost</th>
<th>Stockout consequence</th>
<th>Stockout probability</th>
<th>Stockout risk value</th>
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**Part 2: Optimising values**

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<th>Total stock cost</th>
<th>Stockout consequence</th>
<th>Stockout probability</th>
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<td>M</td>
<td>0.27</td>
<td>39</td>
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</table>

Max stockout prob \( P(x_{id}(\text{max})) \) = 1.00

Condition: \( P(x_{id}(\text{max}) > [1-w_{id}]) \)

Minimize TRV within budget constraint

Minimize TSC subject to acceptable RV

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**Figure 4-2: Minimise Total Stock Cost (TSC) subject to a tolerable level of Total Risk Value (TRV)**
Figure 4-3: Minimise Total Risk Value (TRV) subject to i) a maximum Total Stock Cost (TSC) and ii) a maximum probability of stockout
Discussion

number of parts, $n_{io}$. This constraint is shown in the highlighted box with two concentric circles towards its top right corner in figure 4-3.

In figures 4-1 and 4-2, $P(x_{io})_{\text{max}}$ is mentioned but the value is 1.0. This means that a stockout probability of 100% (a certainty) is acceptable so, in effect, it is not a constraint. Imposing a constraint on the probability of stockout of any type of part when holding an optimised number, $P(x_{io})_{\text{max}}$ (shown in figures 4-3 and 4-4), means that however low impact a failure to meet a demand for a part is, a minimum stock level will be maintained.

Figures 4-3 and 4-4 repeat the optimisation with the same values as in figures 4-1 and 4-2 with the added constraint of $P(x_{io})_{\text{max}}$ = 0.3. As seen in figures 4-3 and 4-4, the additional constraint ensures that however ‘Low’ consequence a part maybe and however expensive it may be, it will be stocked within the stipulated level (0.7 or 70% of expected maximum demand, in this case) of tolerable risk both at a system level (as indicated by Total Risk Value) and at the individual or component level (as indicated by various $P(x_{io})$ values).

However, as shown in the figures, this extra risk mitigation effected by the constraint $P(x_{io})_{\text{max}}$ = 0.3 comes at a price. Figures 4-3 and 4-4 show that the Optimised Total Risk Value $TRV_o$ is now 32 up from 16, and the Optimised Total Stock Cost $TSC_o$ is £375,500 up from £304,500.

The paper in Appendix B shows how $P(x_{io})_{\text{max}}$ impacts $TSC_o$ and $TRV_o$ when $TSC$ is being minimised. [In the paper, (1) $TSC$ as mentioned here is termed as $TSV$ (Total Stock Value) and (2) $P(x_{io})_{\text{max}}$ as mentioned here is termed as $\beta_i(\text{max})$.]
Figure 4-4: Minimise Total Stock Cost (TSC) subject to i) a maximum Total Risk Value (TRV) and ii) a maximum probability of stockout
4.3 DISCUSSION OF THE SPARES MODEL

4.3.1 ASSESSMENT OF THE IMPACT OF NOT MEETING A DEMAND FOR A PART

It is at times difficult to quantify the full implications of not meeting a demand for a part when required (stockout). Therefore, qualitative assessments of consequences or impact of stockout, despite the subjectivity involved, are often the best way to factor in certain intangibles, such as loss of orders or reputation. It is worth noting that the same model will work by directly putting in the likely impact cost (in monetary terms) of a failure to meet a demand for a particular spare.

One can make such estimates more precise by fine-tuning the consequence part of the risk estimate. For example, CoS can be a weighted sum of various consequences factor values such as: extra cost of procuring a part on an urgent basis and the lead time under such circumstances, availability of technical personnel to effect repairs, knock-on effect of failure to meet a part on the general availability of the system and the risk of obsolescence of a part or the machine itself. Figure 4-5 shows how such an approach can be developed.

<table>
<thead>
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<th>Impact Factors</th>
<th>IF1</th>
<th>IF2</th>
<th>IF3</th>
<th>IF4</th>
<th>IF6</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Lead time</td>
<td>Technical staff</td>
<td>Knock-on</td>
<td>Redundancy</td>
<td>Obsolescence</td>
<td></td>
</tr>
<tr>
<td>Weights</td>
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<td>10</td>
<td>20</td>
<td>15</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>Part 1 Assessment</td>
<td>H</td>
<td>M</td>
<td>VH</td>
<td>L</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>6</td>
<td>60</td>
<td>9</td>
<td>4</td>
<td>84</td>
</tr>
</tbody>
</table>

Figure 4-5: Deriving CoS for a type of part from a number of factors
The approach consists of the following main steps:

1. Identify factors (termed as Impact Factors (IF) in figure 4-5) that impinge on failure to meet a demand for a type of spare. In the figure, these are lead time, availability of technical staff, knock-on failures and associated demands, potential for machine or spare redundancy and obsolescence.

2. Ascribe weights to each of these impact factors to reflect their relative importance. These are 10, 10, 60, 15, and 5 for IF1 through to IF5 respectively.

3. Determine relative importance values for VH, H, M, L or VL representing Very High, High, Medium, Low and Very Low. In the approach shown in the figure, these are 100, 80, 60, 40 and 20 respectively.

4. The spare type is then assessed qualitatively- VH, H, M, L or VL - under each of the impact factors identified in step (1). The net result of this exercise is a total Impact Value or the CoS for the type of part under consideration.

In the figure, the value ‘8’ in the first column is (10*80)/100. Weights need to total 100 as this is a relative assessment; the weighted total ‘84’ is the CoS value for that part. This process is repeated for each type of spare part that is under consideration in an inventory. The relative weights or values in step (2) and step (3) may or may not be the same for all parts. Indeed, impact factors also may differ with parts.

4.3.2 THE STARTING ASSUMPTION REGARDING ‘IDEAL’ STOCK LEVEL TO MEET A MAXIMUM DEMAND LEVEL

The starting assumption is necessary to set a baseline. A distinction must be noted: ‘ideal’ values here mean the hypothetical scenario in which the decision maker has no constraints; this is in contrast to optimal values or optimised values that are values that represent optimum
trade-offs, given the constraints that apply. The starting assumption is more in the nature of a carefully thought of scenario considering historical data, expert opinion or guesstimates.

For example, if one has no incidence of a propeller failing in a particular fleet of ships, one might consider a bigger sample or use expert engineering judgement to assess demand. If one was charged with the responsibility of stocking grit for next year’s winter, one reasonable way to start assessing the demand would be to look at what has been the maximum demand in the past, say, five years and use this as a benchmark.

4.3.3 Changes to the Rate of Demand

In the calculations carried out, this model uses a demand trend for each type of part in the period under consideration. The trend is considered fixed in this snapshot in time. The model in its current form is thus based on periodic reviews of the stockholding using prior experience.

The assessment of the demand can be made continuous by using a moving average method for the demand trend. This would represent a continuous review model that may be more advantageous in some circumstances. The model can also be configured to take in statistical distributions other than the discrete uniform distribution in describing the demand for parts.

The rate of demand for parts may well increase as structures or equipment get older. This change in the rate of demand is another factor that could be built into a spares inventory model. It would require a more sophisticated treatment of time dependent effects that is beyond the scope of this work.
4.4 CONCLUSIONS

Research described here applies risk based principles to spares inventory management within the context of life management of offshore structures and equipment. It extends the risk based approach that is well established in other areas of industry. The example illustrates a technique of managing risk within user specified constraints as applicable to spares inventory. The approach outlined here has the potential to increase plant or system availability and manage business as well as operational risks. It is thus of wider interest to a number of other stakeholders including operators, maintenance personnel, regulators and insurance companies, and other industries. The methodology can also be used in other areas that impinge on structural integrity and asset management such as inspection and maintenance where competing risks (of failure) need to be managed within finite resources.
5 DISCUSSION

5.1 APPLICATION OF RISK BASED APPROACHES

Risk based approaches offer a flexible, efficient and rational basis to life management of assets. The previous chapters discussed methodologies that used risk based criteria for decision making in the management of assets. The methodologies were applied in two different contexts: (1) in the undertaking of run-repair-replace decision-making in the management of offshore wind farms, and (2) in the optimal stocking of spares to cater for failures requiring these. Some of the features of the applications of the risk based approaches that stand out are as follows:

(a) The use of risk based optimisation

Risk based optimisation considers three aspects of failures: the likelihood, the consequence and the manageability of failures within the resources available. In the first application in the management of offshore wind farms, the approach shown aims at finding the optimum time of action (repair or replacement), given a budget, such that the cost of such action is less than or equal to the expected cost of failure without that action.

In the second application, risk based optimisation is used to find the optimum number of spares of different kinds a company should advance order such that the cost of holding these spares and the expected cost (risk) of not holding these are within user specified limits.

Risk based optimisation thus takes risk assessment to a more advanced level: from assessing risk to managing risk within the constraints that apply.
(b) Quantitative and qualitative risk models

In both of the above applications, qualitative risk models have been used. In the first application, as a screening tool in order to focus attention on components that are perceived as more at the risk of failure, and in the second, to risk-profile spares such that those that are deemed to have a bigger impact are accorded higher priority in stocking them in an inventory.

Qualitative risk models give a good system-wide perspective and usually involve plant personnel and experts. The screening out of low risk components and the flagging up of high risk component is useful: the identified high risk components can then be analysed using more advanced quantitative methods that usually require more resources. At times, for want of quantitative data, qualitative models are the only option available to risk assessors.

In the application to spares inventory management, a semi-quantitative model using relative risk measures is used. This is to get over the difficulty of quantifying certain factors such as the risk of obsolescence of a spare part. The concept of relative risk helps in profiling the parts using a common denominator for risk.

In engineering there is a justifiable bias towards measuring and quantifying entities. The American Petroleum Institute’s Recommended Practice 580 on risk-based inspection describes a ‘continuum of approaches’ ranging from the qualitative to quantitative, figure 5-1. The figure depicts the level of detail in risk analysis corresponding to a purely qualitative approach on one end of the spectrum, to the purely quantitative one on the other, with intermediate approaches in between. Quantitative models do contain a higher level of details, but the accuracy of the model depends on the availability and the quality of the inputs. Thus in some situations the use of qualitative or intermediate type of models is warranted. The ultimate test of any model is how closely it depicts reality.
Quantitative models can be classified into deterministic models and probabilistic models. Deterministic models have fixed (unique) value inputs that give fixed value outputs. Probabilistic (stochastic) models have inputs that have some randomness described by probability distributions; these distributions reflect the uncertainty or the level of confidence that one has in these inputs. The outputs of such models are also usually in the form of distributions. In the quantitative corrosion model described in chapter 3, the corrosion rate used is a probability distribution. The distribution for the demand for spares in chapter 4 is a uniform distribution.

![Figure 5-1: Continuum of risk analysis models](image)

**5.2 LIMITATIONS AND CONSTRAINTS**

Risk based approaches to asset management enable operators to focus on components where the risk of failure is assessed to be the greatest. The very nature of risk means that these relatively more sophisticated approaches are subject to limitations and constraints, some of which are as follows:

a) Input data relating to failure

To quote from a famous book on risk management (Bernstein, 1996),
“The information that you have is not the information you want.
The information you want is not the information you need.
The information you need is not the information you can obtain.
The information you can obtain costs more than you want to pay.”

In risk based approaches to life management, such as in the management of offshore wind farms and spares inventory, it is assumed that relevant data regarding the mechanisms or observed frequency of failures is available and applicable to the equipment being considered. In practice, a lack of availability and applicability of failure data limits the efficacy of risk based approaches. Sometimes data is not in a suitable format. At times, the failure dataset (sample size) is too small for assessors to extract reliable statistical parameters.

Generic failure databases, (usually from the original equipment manufacturer (OEM) or through generic databases such as, WindStats for onshore wind farms, or the GADS (Generating Availability Data System) from NERC (North American Electric Reliability Corporation) for power generating units), correspond to equipment operated under a range of industry conditions. Sources of information such as logbooks that provide information relating to specific equipment operating under specified conditions, and therefore containing potentially more relevant and applicable data, are often not available. There is an inherent problem in applying generic failure databases to make predictions for specific equipment because the variability of design and operating conditions within the population as a whole may not be representative.

In order to determine the probability of failure from damage mechanisms (e.g. fatigue, corrosion, fracture, collapse, and extreme loads), distributions of the stochastic variables of material properties, loads etc are required. In order to obtain representative distributions, a large amount of experience and/ or experiments relevant to the application may be needed.
These entail the use of substantial resources, and, in practice, the confidence that may be held in such distributions may be questionable.

b) Understanding of the degradation and failure processes

Risk based approaches in the management of structures and equipment are limited by the current understanding of the degradation and failure processes. Although much advance has been made in understanding damage mechanisms such as fatigue, creep and corrosion, more research continues in these and other areas. There are on-going challenges to understand the effect of the operating environment, such as variable amplitude loading on fatigue, the kinetics of different corrosive media (e.g. sour products), and the creep in new alloys and welds.

c) Uncertainty in assessing failure consequences

Apart from the difficulty in assessing the likelihood of failure, the consequences of failure are also at times difficult to ascertain. In some cases, the postulated failure event has never occurred or is a very low probability event and there is therefore no or little prior experience to use. How should one treat extremely low probability but potentially high consequence events? One possible way is to design to fail-safe criteria such that failure does not result in the high consequence under consideration. Low probability- high consequence events are discussed in 5.3, under (c).

Other uncertainties may arise for the following reasons:

i) The impact of failure in complex systems with a number of interactions and correlations is difficult to assess. There may be multiple consequences such as loss of
property, life/injury, environmental damage, clean-up costs, production loss, reputational damage, legal costs and so on.

ii) In systems operating in multiple-jurisdictions where different Class, regulations or laws apply, the consequences of a potential failure may be difficult to assess or open to more than one interpretation. As examples, litigation relating to the 1984 Bhopal gas tragedy in India is still ongoing; nuclear accidents and oil spills may involve a number of countries.

iii) Assessing the consequences of potential failures resulting in the loss of lives is a complex matter. Although insurance companies have methods to quantify such events in financial terms, intangibles such as loss of reputation, loss of morale among employees may be difficult to measure.

d) Requirement for specialist and trained personnel

Engineering analyses, such as numerical modelling, that are often used to determine the probability and consequences of a failure event, usually requires specialist knowledge, skills and computing power. Personnel involved in day-to-day functioning of equipment do not usually have the expertise to conduct such engineering analyses; it may require trained people dedicated to this task in-house and/or expensive consultancy.

e) Technical complexity

Risk analyses can become very complex in a system with many components with interdependencies and correlations in factors affecting failure and its consequences. Often it is necessary to make simplifying or bounding assumptions. It may not be possible to analyse the whole range of failure events each with its set of consequences. Risk models, like other
models, are simplifications of reality; the predictions are subject to potential error. A combination of variables, each having some error, may result in considerable error.

f) Subjectivity in qualitative assessments

Qualitative risk assessments tend to be subjective. To ensure, as far as possible, consistent results, a suitable methodology that is auditable needs to be put in place. Formal processes to elicit expert opinion can reduce the impact of biases that may colour an expert’s outlook.

g) Reliability of inspection and NDT techniques and application

Non-Destructive testing and Condition Monitoring provide vital inputs to the life management of structures and equipment but have their own limitations. Human factors, the probability of detection, the feasibility of sample size are some of the issues involved in inspection and NDT techniques. Condition Monitoring is not considered economical in some situations and the knowledge of the condition of a structure or equipment may not be good or up-to-date.

h) Predicting risk

Risk models identify potential risks and predict failures and their consequences based on some assumptions. It is important to note that these are predictions (expectations or expected values) involving probability and need to be treated as such. At times, events may not occur as predicted. There is a danger of this leading to a general disillusionment with such techniques.
i) Societal awareness of risk

The risk based approaches described here should not be treated in isolation: they need to be a part of a wider culture of risk awareness informing people, processes and technology involved. There is a need to incorporate other perspectives apart from those that result from pure science and engineering analyses. In this context, human factors i.e. the role of humans in failures is a matter of ongoing research. There is also increasing interest in the role of organisation and its structure in managing risks.

j) Managing risks optimally, not just cutting costs

The philosophy behind risk based approaches is to optimise resources in the management of risks; the aim is to focus resources on components identified as having high risk of failure. Although a successful risk based approach will reduce failures and hence the costs resulting from failures, it is not and should not only be construed as a part of cost cutting exercise in the management of assets.

k) Upfront costs in managing risks

Reducing the level of risk often entails upfront costs that can be justified only in the long run; risk mitigation thus needs foresight and the ability to invest in a safer future even if this means foregoing immediate gains. Some companies are not prepared to make the investment in risk based approaches.

l) Recognition of risk management professionals within business

Risk management professionals become the focus of attention particularly when bad things happen or when risk management systems fail. They need to be taken seriously even during
normal times and, indeed, be rewarded for continued safe operations. Some companies do not sufficiently value their risk management professionals.

5.3 FURTHER DEVELOPMENTS

Research undertaken for this thesis shows that notwithstanding the limitations and constraints identified above, there is scope for further development within the field of risk based life management of structures and equipment. Some of the areas for development are described below:

(a) Improving the quality (precision) of input data to risk assessment.

Recent advances in equipment monitoring and better ICT (Information and Communication Technologies) are improving the quality of failure data that is being available for life management of structures and equipment. Operators increasingly find it in their interest to share failure data and there are a number of failure databases being set up to achieve this. The RISPECT (Risk Based Expert System for Through-Life Structural Inspection, Maintenance and New-Build Structural Design) project is an example of a number of stakeholders in the shipping industry coming together to share inspection and failure data. RISPECT involves the setting up of a hierarchy of databases (mainly comprising ship managers’ databases, classification bodies’ databases and a central statistical database) containing relevant shipping data and a number of modules that perform risk and reliability calculations using this data (The website http://www.rispect.org.uk/ contains more information). Other databases containing failure data such as WindStats and NERC-GADS are the result of collaboration between various stakeholders in the relevant industry sector.
(b) Greater understanding of degradation mechanisms

With increasing experience and research, there is a trend of having a greater understanding of the degradation mechanisms involved in the ageing of assets. For example, understanding of fatigue requires experimental data. Faster computers have made it easier to make complex calculations and build complex models to link experiment to reality. The variability in the action of degradation mechanisms and the correlations between them are increasingly being calculated.

(c) More attention on towards low probability- high consequence events

There is increasing interest in low probability and high consequence events. Such events are difficult to manage as: a) these are by definition extreme events, hence experience of dealing with them is not always sufficient to draw lessons from and build a model on, and b) these events are often so rare that measures to prevent/ mitigate such individual unlikely events are not deemed cost-effective.

Concerted action to deal with extreme events that have common severe consequences is often seen as a feasible way to prepare for such events. Industries have formed special networks to pool resources to prepare for such rare adversities. For example, a group made up of the ICE (Institution of Civil Engineers), the Royal Institute of British Architects, the Royal Institute of Chartered Surveyors, the Royal Town Planning Institute and the Landscape Institute, works together to manage and mitigate floods. The Fire and Blast Information Group (FABIG) is the result of offshore industry collaboration, following the Piper Alpha disaster, to collate and disseminate existing knowledge on hydrocarbon fires and explosions.
Governments too form special committees that include representatives from law enforcement bodies, the medical fraternity and others to respond to crises that are rare but require these common resources.

Should every low probability- high consequence event be protected against? A balance is required between risk mitigation and acceptable consequences. Typically, a risk assessment is required to identify mitigation and acceptable costs. Some extremely low probability events may remain unforeseen and therefore not a part of any risk assessment model; the best approach in such circumstances is often to focus on responding to the new situation such that the impact of such event is minimized.

(d) New applications of risk based methods

Risk based methods are being used in a variety of areas in industry. For example, there is interest in using such risk based techniques to optimise inspection and maintenance in ships and FPSO vessels.

(e) The need for a holistic approach to risk management

There is increasing interest in taking a holistic view in managing risks. This includes better integration and coordination between people, processes and technology. This is done through, as examples, better training, policy-making and guidelines in handling interfaces within and between systems.

(f) Stakeholders in risk management
Risk based approaches are, in large part, driven by the operators’ desire to allocate resources in a flexible, rational and an efficient way. However, their application is also influenced by legal and social forces. The role of regulation in the use of risk based approaches is gaining prominence. Public awareness regarding risk and its management in industry has never been higher.
6 CONCLUDING REMARKS

The following sums up the main points from the research undertaken within the remit of this Doctor of Engineering thesis

1. Research presented here describes new applications of risk based approaches to two specific decision making situations involving the life management of structures and equipment:

   (a) Given a failure trend, when is the optimum time of action (repair/replace a structure or equipment) such that the net cost of the action and the expected cost (risk) of failure is minimised and hence financial efficiency optimised? The particular application was maintenance optimisation in the life management of offshore wind farms.

   (b) How many parts of different kinds, with each having its own associated stocking costs and stockout risks, should a major industrial enterprise advance order for stock to operate at optimum efficiency given that failures (requiring these) may occur in service? The particular application was a fleet of cargo ships where parts of different kinds are required to keep ships available for service.

2. The optimisation techniques in risk management described in this thesis find the optimum trade-off between the cost of a risk mitigating measure and the expected cost (risk) of failure without that measure. They have the potential of being applied more widely within structural integrity and asset management, and indeed in any situation where competing risks need to be managed within finite resources. They may therefore find application in areas such as risk based inspection and maintenance, and more generally, in other areas of risk management in engineering.
3. The nature of risk poses a number of challenges to its assessors. Uncertainty in input data is likely to remain a limitation. The question then is how this uncertainty in data is accounted for in a risk assessment. The bottom-line in any assessment of risk is the application of scientific method to the maximum extent possible and the continual testing of prediction against empirical data.

4. The application of risk based approaches to life management of assets is a relatively recent development. It is expected that in an increasingly competitive environment the uptake of these approaches will become more prevalent in industry. This is because risk based approaches offer rational, efficient and somewhat flexible ways of maintaining assets.
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APPENDIX A : PAPER 1

ABSTRACT

Offshore wind farm managers are under increasing pressure to minimise life cycle costs whilst maintaining reliability or availability targets, and to operate within safety regulation. This paper presents a risk based decision-making methodology for undertaking run-repair-replace decisions with the ultimate aim of maximising the Net Present Value (NPV) of the investment in maintenance. The paper presents the methodology developed for the risk based life management of Offshore Wind farms under the remit of the CORLEX (Cost Reduction and Life Extension of Offshore Wind Farms) project funded by DTI (Department of Trade and Industry, UK) Technology Programme on Renewable Energy.

Unlike traditional approaches to decision-making that consider either the probability of failure of a component or the consequence of failure in isolation, a risk-based approach considers both these aspects in combination to arrive at an optimal solution. The paper builds a basic Qualitative Risk Analysis methodology to highlight high-risk components that
are then investigated further by a Quantitative Risk Analysis. The risk is now quantified in monetary terms and the time of action – replacement or maintenance- indicated by the model is such that the NPV of the action is maximized. The methodology is demonstrated by considering offshore wind turbine tower as the critical component and corrosion as the damage mechanism.

Keywords: Offshore wind farms, Maintenance, Risk Based Decision Making, Quantitative Risk Analysis.

1 INTRODUCTION

Maintenance manages the process of ageing of a plant or machinery. Ageing is a process that is relentless and starts from the moment a product is manufactured or fabricated. The rate of failure versus time relationship is usually depicted by Figure 1. During the initial stage- the Infant Mortality stage, there are ‘teething’ problems causing the failure rate to be high. The rate than falls as these problems – design, manufacturing defects, etc are identified and solved. In the second stage, which is the Useful Life stage, standard maintenance practices keep the failure rate almost constant. During the third and final stage of the plant- the Ageing stage, the failure rate rises mainly due to damage accumulated by ageing. At some point during this stage, high failure rate requires operators to consider replacing the plant. In practice, there are usually a number of such plants and a limited budget available to decision makers.

This paper develops and demonstrates a risk-based methodology to decide the optimum time of replacement or repair of a plant, given, a number of such plants, and limited budgetary support.

The paper starts with a discussion on risk and its analyses- qualitative and quantitative, the concept of NPV, and moves on to the trade off involved in risk-based decision-making within budgetary and safety constraints.

2 RISK

Risk has numerous definitions depending upon its use. Risk is a combination of the probability of an event and its consequence. (API 2002) It is a
deviation from the normal or expected. Numerically, it is a product of probability of an event occurring and the consequence of the event.

3 THE RISK BASED APPROACH TO MAINTENANCE

A risk-based approach considers failure in both its dimensions, taking cognizance of the two elements that constitute risk- the probability (or likelihood) of failure and the consequence of that failure. Figure 2 shows the two dimensional risk profiles of the components in an offshore wind turbine plant henceforth referred to as the plant.

The probabilities and the consequences of failure of ten components have been determined and presented as points on a Risk Plot. An iso-risk line is also plotted representing a constant risk level as defined by the operator according to their perception of what is an acceptable threshold level of risk. The iso-risk line separates acceptable risk components from the unacceptable risk components, enabling plant managers to focus maintenance resources on the relatively more risky components.

Risk analysis is the systematic use of information to identify sources of risk, and to estimate the risk of failure. It forms the basis for risk evaluation, risk mitigation and risk acceptance (or risk avoidance). The information used in risk analysis includes historical data, theoretical analysis, informed opinions and stakeholder concerns.

4 RISK ANALYSIS METHODS

Risk analysis methods are generally categorised as qualitative or quantitative. There may be an intermediate category (semi-quantitative) depending upon how quantitative the risk analysis is. The American Petroleum Institute’s Recommended Practice 580 on risk-based inspection describes a ‘continuum of approaches’ ranging from the qualitative to quantitative, Figure 3. The figure depicts the level of detail in risk analysis corresponding to a purely qualitative approach on one end of the spectrum, to the purely quantitative one on the other, with intermediate approaches in between.
4.1 Qualitative Analysis

This method uses engineering judgement and experience as the basis for risk analysis. The results of the analysis largely depend on the expertise of the user. The primary advantage of qualitative risk analysis is that it enables assessment in the absence of detailed numerical data. It is also the first pragmatic step to conduct a quantitative risk analysis by screening out components of less concern. Moreover, the results can serve as a reality check on the outcome of quantitative analysis. However, it is not a very detailed analysis and provides only a broad categorization of risk. Failure Modes, Effects and Criticality Analysis (FMECA), Hazard and Operability Studies (HAZOPS), and the Risk Matrix approach are examples of qualitative risk analysis. In the Risk Matrix (API Publication 2000) approach, the likelihoods and consequences of failure are qualitatively described in broad ranges (e.g. high, medium or low). Figure 4 shows the risk profiles of selected components of a wind turbine plant. The risk profiles are for demonstration only: in practice, the profiling is done by involving plant experts.

4.2 Quantitative Analysis

Qualitative risk assessments become less discerning when the system complexity increases, so quantitative analysis is usually required the risk discrimination of a system of components. Quantitative Analysis assigns numerical values to the probability (e.g. 10-5 failure events per year) and the consequences of failure (e.g. inventory released over 1,100m2). Qualitative Analysis techniques such as FMECA and HAZOPS can become quantitative when the values of failure consequence and failure probability are numerically estimated. The numeric values can determined from a variety of references such as generic failure databases, elicited expert opinion, or calculated by specific engineering and statistical analysis. (ASME International 2003) There are statistical methods for combining data from various sources or updating data with additional information. (Jordan 2005)(Kallen, Noortwijk 2005)(Khan, Haddara & Bhattacharya 2006)
In the current discussion, it is assumed that the structure of a wind turbine tower is of critical importance, as highlighted by the Qualitative Analysis in the previous section.

For the Quantitative Risk Analysis method proposed in this paper, a failure frequency versus time curve, for the Ageing period of life is developed by engineering analysis of the structure for the active or potentially active in-service damage mechanisms, e.g. corrosion. The consequence of failure is in financial terms. For complex systems, event tree analysis is usually undertaken to determine the effect the particular component has on the system, to thereby resolve the individual cost of consequence of the component’s failure.

5. RISK BASED OPTIMISATION

The next step is the calculation of the optimum action schedule or date, of the run-repair-replace action. This calculation weighs the financial benefits of maintenance action against the risk (as expressed in costs) of not taking the action. The ultimate aim is to maximise the net present value of the investment (i.e. the maintenance action) by adjusting the date of the action.

6. DECISION-MAKING USING FINANCIAL CRITERION

6.1 The need for financial criterion in maintenance decision making

Maintenance projects are increasingly being evaluated by decision makers who need to understand the implications of various options in financial terms. Although predictive maintenance techniques have matured, the predictions are in engineering terms, and these are not easily understood by financially oriented decision makers. Thus, there is a need to express the effects of engineering wear and tear in financial terms. In the current context, this is done by evaluating the cost of the consequences of failure owing to wear and tear of plant and machinery.

6.2 The drivers for a consistent decision making methodology in maintenance
Many old plants, structures, capital equipment or components are in their Ageing period of life. However, increasing competition means many of them cannot be replaced and need to have their useful life extended. In addition, new components are often designed to operate with maximum efficiency, and are designed with lower “margins of error” against assumed operating conditions.

Each action (or project) has costs associated with it. These costs are, in essence, investments made by the concerned asset owner with the expectation of certain return on the investment(s). The decision maker will normally be faced with a number of projects competing for such investments, and therefore needs to take decisions that maximise the returns on these investments. The most widely understood financial techniques to evaluate projects include ‘return on investment’, ‘pay-back period’ and ‘discounted cash flow (DCC)’ methods. (Brealey, Myers 1991) These techniques have various strengths and weaknesses. This paper employs the net present value (NPV) technique that is a form of DCC analysis.

7. Maximizing NPV using Probabilistic Damage Mechanism Models

7.1 NPV Financial Analysis

In the current discussion, it is assumed that a project with a higher NPV is a better investment than a project with a lower NPV. The NPV of a project is the present (current) value of the total future cash flows, both positive (income) and negative (cost). NPV considers the time value of money by discounting all the cash flows, and it is calculated as follows:

\[ NPV = \sum_{t=0}^{N} \left( \frac{C_t}{(1 + r)^t} \right) \]

\[ N = \text{project life (years); } t = \text{timing of cash flow (year); } r = \text{interest rate, or discount rate; and } C_t = \text{cash flow in year } t. \]
The future cash flows are ‘expected’ cash flows, as they do not occur with certainty. The uncertainty arises in the engineering analysis to calculate the probability of failure over time for the damage mechanism(s) of interest.

The risk associated with any project is finally expressed in terms of its NPV by using expected values (EV). The EV of a failure event is the product of the probability of the event occurring and the cost of consequence of that event.

The cost of consequence of a failure event is directly assessed from a prior quantitative consequence analysis, and it must be expressed in financial terms.

Thus, the NPV of a project with uncertain outcomes is the sum of the expected values of all future discounted cash flows, as follows:

\[
NPV = \sum_{t=0}^{\infty} (p_t \times C_t) / (1 + r)^t
\]  

\( p_t \) = the probability of the event occurring at time \( t \).

7.2 Probabilistic Damage Mechanism Model

This paper does not discuss the details of damage models for use in probabilistic analysis. Instead it illustrates a simple probabilistic damage mechanism model for general corrosion of the tower structure. Consider a structure subject to corrosion. Assuming this to be the only damage mechanism causing failure of the structure, the remaining life of the structure can be calculated as:

\[
RL = (T_c - MAT) / CR
\]

(3)

\( RL \) = remaining life (years); \( T_c \) = current thickness of the structure (mm); \( MAT \) = minimum allowable thickness (mm); and \( CR \) = corrosion rate (mm/year).

CR is derived from periodic in-service measurements of metal loss resulting from corrosion.
Tc is known from the most recent thickness measurements on the structure (or at the start of the structure’s life, Tc can be assumed to be equal to the original nominal thickness of the structure as specified by the designer including tolerances, corrosion allowance, etc). MAT is the absolute minimum thickness calculated by the designer to prevent failure by overload, collapse, etc as appropriate.

The convention is to calculate RL in a deterministic manner, whereby each independent variable in Equation 3 is a specific value. This assumes that these variables have no random or probabilistic aspects but can be defined in a fixed predictable fashion. In reality, there is considerable uncertainty associated with these variables and each can be defined by a statistical distribution of values.

In the method here, a statistical analysis tool (i.e. Palisade’s @RISK for Microsoft Excel) is used to describe all the independent variables probabilistically, and RL is then calculated using Monte Carlo Simulation (MCS) technique. In this way, the calculated RL by MCS is actually a distribution of values, so that the annual probability of failure (the failure rate per year) over time can be obtained. This probability versus times curve may then be used to derive the EV, where the EV of a failure event is the product of the probability of the event occurring and the cost of consequence of that event, at a specific point in time.

### 7.3 Risk-based Optimisation

The key inputs to the optimisation model are as follows:

(a) The expected present value of the proposed action (replacement or repair of the asset); (b) The expected present value of inaction which is equal to the expected present value of the production losses avoided as the result of undertaking the proposed action; (c) Any financial constraints, such as the annual maintenance budget limit; and (d) Any non-financial constraints, e.g. on failure rates due to safety regulations.
Thus, for the NPV of an action taken at time \( t=n \), the following can be defined:

\[ \text{CB}_t = \text{Cash flows associated with production in year } t; \]

\[ \text{CP}_t = \text{Cash flows associated with implementing the project in year } t, \text{ including any tax credits (positive cash flow) on depreciation costs;}(\text{Collier, Glagola 1998}) \]

\( N = \) the maintenance planner’s strategic planning period;

\( n = \) year in which the action is proposed to be undertaken;

\( p_t = \) probability of the event (failure) occurring in year ‘t’; and

\( r = \) interest rate, i.e. the cost of money (finance).

In the current context, the NPV of action in any year ‘n’ is given by:

\[ \text{NPV} = (\text{Expected present value of action}) + (\text{Expected present value of inaction}) \] (4)

Assuming that cash outflows are negative and cash inflows are positive, and failure results in production loss,

\[ \text{NPV} = -\left[ \sum_{t=0}^{t=n} \text{(CP)} \times (1+r)^t \right] + \]

\[ - \sum_{t=0}^{t=n} (p_t \times \text{CB}_t) + (1 + r)^t + \sum_{t=n+1}^{t=N} (p_t \times \text{CB}_t) + (1 + r)^t \] (5)

The optimization algorithm calculates the year of maintenance action for which the NPV is maximum (least negative), subject to stipulated constraints.

The maintenance action may be replacement or repair. In case of replacement, the equipment/component begins its life cycle from its Infant Mortality Stage through to the Ageing Stage. In the current model, it is assumed that repair improves the condition of the equipment such that it returns to a stage prior to the Ageing Stage i.e. the Normal Life Stage or, preferably, the Infant Mortality Stage.
8. In-service Inspection Optimisation

The model could be extended to ‘inspection’ actions. Instead of the replacement cost of the component, the cost of in-service inspection would be considered. Since such actions (projects) are usually accounted for as ‘expenses’ in the year in which they occur, rather than as ‘investments’ (which would then be written-off over several years), tax credits from depreciated costs do not arise. Since inspection costs are relatively low compared to production losses, it is anticipated that the model would suggest the optimum year of inspection is the first year of the planning period. To address this, the American Society of Mechanical Engineers (Risk Based Methods for Equipment Life Management, CRTD Vol 41) has provided the following course of action to optimise in-service inspection dates:

Optimise the action date, assuming the inspection cost is equal to the replacement cost; then

Inspect the equipment before this calculated replacement date; then

Compare the actual component damage found during inspection, to the projected conditions; and then

Replace the component if necessary, or re-calculate a new optimized action date, assuming the inspection cost is equal to the replacement cost.

It is also possible to add value to the overall replacement decision-making in the Ageing period of life, by scheduling in-service inspections without the use of the model. Inspection findings may be used to revise the rate of damage (e.g., corrosion rate, CR), or corrective action can be taken to reduce the rate of damage (e.g. maintenance painting to eliminate corrosion). Using the model described above, the NPV of such an action can then be compared with the NPV without such action, to appraise the inspection financially.

9. Demonstration of the Model

The approach described above was successfully demonstrated by evaluating three offshore wind turbine towers (i.e. the structures, and not the
rotating machinery). The failure frequency from a probabilistic corrosion model is presented in Figure 5. The optimised replacement schedule for Structure #1 is shown in Figure 6. The year in which the ‘ActionCost NPV’ is maximum has been calculated. NPV is obtained by considering the expected net present value of: (a) cash flows resulting from the replacement of the structure; (b) the avoided lost production outage cost due to replacement. The optimum action date for Structure #1 is 2013, Figure 7.

Figure 7 shows the application of risk based approach to maintenance of Structure #1. The probability of failure versus time curve derived from remaining life estimates on its own is incomplete information to the decision maker. The Action NPV versus time curve generated by the risk based approach enables the user to make a more informed maintenance decision by considering the consequences of failure too, in conjunction with the probability of failure. The optimal action date is the time when the NPV of the action is maximum (2013, for Structure #1).

The optimized action years for the other two structures are derived in the same way. To determine the optimised action years for all the three structures within a budgetary constraint, the Solver in MS Excel was used. The resulting optimised schedule is shown in Figure 8.

Figure 8 shows the replacement schedule for three structures Str#1, Str#2 and Str#3 as 2013, 2016 and 2014 respectively.

10. Limitations of the model

Some of the immediately apparent limitations of this tool are as follows:

For more complex systems with increasing number of components and constraints, non-linear optimization tools (i.e. based on genetic algorithms) more powerful than the linear Solver in Microsoft Excel may be required;

There are economic dependencies in maintenance and inspection, so with increasing dependencies, the methodology will become more
complex and more computing power may be required for the analysis; and

For safety critical systems, as opposed to business critical systems, where the target or acceptable levels of failure probability are of the order of $10^{-4}$ to $10^{-6}$ failures per year, the constraints on the failure probability may be so severe, as to cancel out any potential financial benefits from applying the methodology.

This methodology is essentially for proposed action during the ‘Ageing Phase’ of a plant in which failure is primarily due to accumulated damage. Thus the method needs to be used in conjunction with an overall maintenance strategy rather than in isolation.

11. Conclusions

The paper describes and demonstrates work in progress of the DTI funded CORLEX project under the Technology Programme on Renewable Energy.

Risk-based maintenance optimization requires a detailed analysis using quantitative techniques. The proposed methodology uses engineering analysis by developing a basic probabilistic damage mechanism model to obtain failure rates. The resulting failure rates over time, are used to calculate expected present values of cash flows before and after selected maintenance actions (e.g. equipment replacement).

It has been shown that the optimum year of replacement can be calculated when the net present value (NPV) of the maintenance action is maximised. If there is a budgetary constraint that does not allow for a series of actions in a system of structures to be undertaken in a given strategic planning period, multi-component optimisation can be easily undertaken using the approach.

Future work will focus on the derivation of failure rates using expert elicitation, as well as the combination of failure probabilities using Bayesian methods to update prior probability distributions with other data sources, e.g. generic failure databases with expert knowledge. The optimisation method currently used in the method will also be developed by exploring the practicalities of using off-the-shelf genetic algorithm solvers. Finally, further work will be undertaken to incorporate a wider range of in-service equipment damage mechanisms, as well as
previous in-service inspection data, to optimise future inspection plans (i.e. coverage and schedule).

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ANNEX A

FIGURES

Figure 1: Failure rate of plant components versus age.

Figure 2: Idealised Risk Plot of several components within a plant.
Figure 3: Continuum of Risk Analysis methods.

Figure 4: Qualitative Risk Analysis using a Risk Matrix
Figure 5: Probability of failure versus time

Figure 6: Optimum time of replacement of Structure #1
Figure 7: Structure #1, Action NPV and Probability of Failure versus time

Figure 8: Optimum schedule of replacement of three structures within budgetary constraints
A RISK BASED METHODOLOGY FOR SPARE PARTS INVENTORY OPTIMISATION

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ABSTRACT

Spare parts inventories assist maintenance staff to keep equipment in operating condition. Thus the inventory level of spares has a direct bearing on machine availability, a factor that is increasingly important in capital-intensive industries. This paper presents a risk based approach for spare parts inventory optimization.

At the outset, the paper highlights the unique features of maintenance inventories, such as spare parts inventories, compared to other inventories such as work-in-progress or finished product inventories. After a brief mention of the principles on which many of the current inventory management models are based and their limitations, the paper presents a risk-based methodology to spares inventory management. ‘Risk’ in the current context is the risk in
monetary terms that arises when a component (spare) is not available on demand. It is the expected value of loss, i.e., the product of the likelihood of unavailability of the spare from the inventory and an estimate of the consequence(s) of that unavailability. Given a budgetary constraint and the risk profile of a number of spares, the model gives an optimal inventory of spares.

By basing the inventory on the risk profile of spares, the model includes factors that are not normally considered in various other models. The ultimate aim of the methodology is to have an optimal level of spares inventory such that machine availability, to the extent it is dependent on the level of spares inventory, is maximized subject to constraints. The methodology is expected to benefit both, operational and financial managers.

1.0 INTRODUCTION

The level of spares in an inventory has a direct bearing on machine availability. The availability of a machine is a function of the mean time to correct a failure which in turn depends upon, among other factors, the time to obtain a spare (to conduct repairs) or a replacement. The level of spares in a spares inventory is constrained by the cost of holding stock and the penalty of being out of stock. In a competitive climate companies strive to keep their spares inventory at an optimum level to minimize the costs involved. This paper presents a new approach - a risk based approach - to spares inventory management aimed at establishing an optimum level of spares such that financial benefit is maximized within accepted levels of risk, and the remaining (residual) risks are clearly identified. The paper presents a framework that enables consistent and auditable decision making in spares inventory management.
Risk based approaches are used in other sectors of industry and for prioritizing different
types of actions; for example, there are risk based approaches in the process industry to manage
maintenance and inspection and there are standards or guidance documents to implement these
approaches (1, 2, 3 and 4). As opposed to other approaches, in a risk based approach, actions are
based on the risk estimate of various options. In the current context, this means maintaining an
inventory at an optimal level depending on the risk profile of the spares in which the likelihood
of a failure to meet the demand for a spare is considered in conjunction with the consequences of
the failure to meet that demand. The optimal level is such that financial benefits are optimized
given risk associated constraints.

The paper discusses some of the unique features of spares inventories vis-à-vis other types of
inventories. There is also a section on typical costs associated with inventories followed by a
brief note on the main principles underlying various current approaches to spares inventory
management. The main body of the paper then presents the risk based methodology and the basic
model that has been created to implement that methodology. This is followed by limitations of
the methodology, areas of further research and conclusions.

2.0 SPARE PARTS INVENTORIES

Spare parts inventories are maintenance inventories; they are used by maintenance personnel
to keep machines available and exist to meet an internal demand for spares. They perform a
different function compared to other inventories such as Work-in-progress (WIP) inventories and
Finished Product Inventories. WIP inventories smooth out irregularities in production flow. These
irregularities are caused by factors such as changes in product mix, equipment breakdowns,
differences in production rates, between processes and material handling. Finished Product
Inventories provide a buffer stock to protect against lead time demand, differences in quality levels, differences in machine production rates, labor troubles, scheduling problems, gap between capacity and demand and other well established production problems (5).

Characteristics of Spare parts inventories: Spares Inventories are hugely influenced by maintenance policies rather than customer usages that dictate WIP or Finished Product Inventories. For scheduled maintenance, the demand for spares is relatively more predictable and it may be possible to order parts to arrive just in time for use and indeed not stock such parts at all. For unplanned maintenance, a lack of some safety stock often means that the consequences of not keeping some safety stock include production loss. There are other factors such as the amount of redundancy within a system, availability of reliability information from condition monitoring equipment, dependency of failure events, possibility of demands being met by cannibalism and the effect of parts or machine obsolescence on the level of stock holding. There has also been research illustrating how other factors such as the organizational context of inventories, especially the responsibilities and authorities of the persons concerned, have a bearing on inventory management (6).

3.0 SOME TYPICAL COSTS ASSOCIATED WITH INVENTORIES

Ordering and setting up costs: These are fixed costs that do not depend on the size of the order. For example, ordering costs would include paperwork and billing associated with the order. For parts made in-house, ordering and set up costs would include the cost of labor, setting up and shutting down the associated machinery.

Unit purchasing cost: This is the variable unit cost of a part or a component. If the part is manufactured in-house, It includes the variable labor cost, the overhead cost, and the raw material
cost needed to produce a single unit. If this part is ordered from an external source, then the unit purchase cost must include the shipping cost.

Holding or carrying cost: These are essentially the inventory costs expressed in monetary value per unit part per year. It includes storage cost, insurance cost, taxes on inventory, and cost due to the possibility of spoilage, theft, or obsolescence. However, usually the most significant of the holding cost is the opportunity cost incurred by tying up capital in inventory. The opportunity cost is the return the company would expect on an investment elsewhere rather than in stockholding.

Stockout costs: When a demand for a product or a part is not met on time, a stockout is said to have occurred. If it is acceptable for demands to be met at a later date, no matter how much later, it is said that demands may be back-ordered. In the current context, Risk is the combination of the probability of a stockout event and its consequence, where a stockout is an event in which a spare is not available on demand. If it is necessary for demands to be met on time, and if this is not achieved, then the scenario is a lost case one. In the current context, a lost case may result in production loss, regulatory penalty and other consequences such as loss of goodwill. Usually it is more difficult to measure the cost of a stockout rather than ordering, purchasing or holding costs.

4.0 APPROACHES TO INVENTORY MANAGEMENT

There are different approaches to Inventory Management. SM categorizes inventory models into two: Economic Order Quantity (EOQ) and Materials Requirement Planning (MRP). Under these, he classifies about ninety inventory models (7). WW classifies models as Deterministic EOQ Models, Probabilistic Models and other recent models such as MRP, JIT and Exchange
Curves (8). SN looks specifically at repairable inventory systems and classifies existing models into three general classes: continuous review, periodic review and models based on cyclic queuing systems (9). The Risk Based approach presented here is unique in that it does not completely fall in any of these categories although it might have some elements of the approaches listed above.

5.0 THE RISK BASED APPROACH TO SPARE PARTS INVENTORY MANAGEMENT

The Risk Based approach to Spares Inventory Management presented here is consistent with risk based decision making approaches used elsewhere, for example, in maintenance and inspection planning within the process industry.

In the current context, the following terms have a special meaning: Risk is the combination of the probability of a stock out event and its consequence where a stockout is an event when a spare is not available on demand. Qualitative Risk Analysis broadly covers methods that use engineering judgment and experience as the bases for the analysis of probabilities and consequences of failure. Failure Modes, Effects, and Criticality Analysis (FMECA) and HAZOPs are examples of qualitative risk analysis that become quantitative risk analysis when consequences and failure probability values are estimated. Quantitative Risk Analysis a) identifies and delineates the combinations of events that, if they occur lead to an undesired event b) estimates the frequency of occurrence for each combination c) estimates the consequences. The approach shown here is a semi-qualitative approach that captures best estimates from experts as well as raw historical data. The risk referred here is relative risk which is a comparative risk of components or equipment in relation to each other.
In the method described below, a risk profile of the spares is obtained by considering the likelihood of a failure to meet the demand for a spare in conjunction with the consequences of the failure to meet that demand. This risk profile is then used to find the optimal level of inventory such that financial benefit is maximized given an identified acceptable risk level.

6.0 A BASIC MODEL TO IMPLEMENT THE APPROACH

6.1 Underlying concepts

The model has two parts: Part 1 establishes baseline values, and Part 2 optimizes values. The implementation of the approach is shown by way of an example shown in Figure 1.

Part 1: Obtaining baseline values:

This part of the model aims at establishing baseline values for certain parameters for the purpose of optimizing in the second part of the model. The parameters with their descriptions are as follows:

\( i = \) unique part number for identification;

\( F_i = \) Expected failures in a planning period based on historical data, expert opinion, generic data or a mix of these. There are guidelines/procedures for combining data from various sources. (10) and (11);

\( \alpha_i = \) ratio of part \( i \) in stock to the expected demand depending on \( \alpha_{i(\text{ref})} \);

\( \alpha_{i(\text{ref})} = \) reference (baseline) value of \( \alpha_i \) for planning purpose;

\( n_i = \alpha_{i(\text{ref})} \times F_i = \) number of parts held in stock, rounded to the nearest integer;
\( C_i = \text{net unit cost of part } i \);  

\( CoF_i = \text{consequence of a stockout for part } i \);  

\( \beta_i = \text{Stockout frequency estimate for part } i, \text{ assuming stock outs are proportional to stock levels} \)

\[
\beta_i = 1 - \frac{n_i}{F_i} \quad \text{...Eq. 1}
\]

\( RV_i = \text{Risk value associated with part } i \)

\[
RV_i = (\text{Quantified } CoF_i) \times \beta_i \quad \text{...Eq. 2}
\]

\[
TSV = \sum n_i \times C_i \quad \text{...Eq. 3}
\]

\[
TRV = \sum RV_i \quad \text{...Eq. 4}
\]

In the model shown below, qualitative estimates of \( CoF_i \), VH, H, M, L, VL have been assigned values 100, 80, 60, 40 and 20 respectively. In a more advanced model, these values would be a weighted average of values obtained by considering a number of consequence or impact factors. One such possible scheme is shown in the Appendix.
Figure 1: A basic Risk Based Spares Inventory Management Model

Part 2: Obtaining optimized values:

This part of the model contains optimized values obtained after using a linear optimizing tool using the values in Part 1 of the model, wherever applicable. The optimized values contain the subscript ‘o’. For example, $n_{io}$ is the optimized value of units of part $i$ to be held in the inventory.

<table>
<thead>
<tr>
<th>Part 1: Establishing baseline values</th>
<th>Part 2: Obtaining optimized values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected value</td>
<td>Baseline value</td>
</tr>
<tr>
<td>$n_i$</td>
<td>$n_{io}$</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
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<td>5</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>17</td>
</tr>
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<td>7</td>
<td>14</td>
</tr>
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<td>8</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

Max stock value acceptable: $4.5M$
Max stockout acceptable/year: 10

---

9 Copyright © 2008 TWI Ltd
6.2 Working of the model:

At the outset, in Part 1 of the model, an appropriate value for \( \alpha_{i(ref)} \) is assumed; in Figure 1, this is 0.95. \( \alpha_{i(ref)} \) is a percentage of the expected spare parts demand, necessitated by failures, to be held in the inventory. This starting assumption is necessary to find baseline values for Total Stock Value (TSV) and the Total Risk Value (TRV) of the inventory, say, \( TSV_b \) and \( TRV_b \) respectively where,

\[
T SV _b = \sum n_i \times C_i \quad \ldots \text{Eq. 5}
\]

\[
TR V _b = \sum R V_i \quad \ldots \text{Eq. 6}
\]

The values above are, in essence, baseline or reference values that establish what is an acceptable level of overall risk and the associated cost of stock holding at that level. Having established these baseline values as a starting point, we then move on to Part 2 of the model in which linear optimization is carried out. In the model demonstrated here, the Linear Programming is through the Solver add-in to Microsoft Excel.

Linear programming:

Linear Programming (LP) is a tool to solve optimization problems. Since the development of the simplex algorithm by George Dantzig in 1947, LP has been used extensively in academia and industry.
Formally, a LP problem is an optimization problem for which we do the following:

i) We attempt to maximize (or minimize) a linear function of the decision variables (variables that describe the decisions to be made). The function that is to be maximized or minimized is called the objective function.

ii) The values of the decision variables must satisfy a set of constraints. Each constraint must be a linear equation or a linear inequality.

iii) A sign restriction is associated with each variable. For any variable $x_i$, the sign restriction specifies either that $x_i$ must be nonnegative ($x_i \geq 0$) or that $x_i$ may be unrestricted in sign. (12)

The optimization here is as follows:

Minimize $TSV$ such that $TRV \leq TRV_b$

All values are integers and greater than zero. The optimized values for TSV and TRV are $TSV_0$ and $TRV_0$ respectively.

The Table shows values corresponding to two values of $\alpha_i^{(ref)}$, 0.95 and 0.90. Consider the first row in the Table. This scenario is captured by Figures 1 and 2.

Figure 1 shows the risk profile of the various components in the last column. Individual values of stockout consequence and frequency estimates can also be seen. Figure 2 graphically depicts the risk profile before and after optimization.
As shown in the above Figures 1 and 2, although optimization has been carried out as described, there may be some components for which the risk profile may be considered too high to be acceptable to the decision maker. For example, the RV for part 3 i.e. $RV_3$ is 20; this is a part of VL consequence, but the likelihood value of a stockout is very high at $\beta_{30} = 1.00$. Such a value may be deemed too high by the decision maker especially when it is substantially different to $\alpha_{i(ref)}$ that was assumed initially in Part 1 of the model.

Table: Baseline Values and Optimized Values

<table>
<thead>
<tr>
<th>$\alpha_{i(ref)}$</th>
<th>$TSV_p$</th>
<th>$TRV_p$</th>
<th>$TSV_o$</th>
<th>$TRV_o$</th>
<th>$\beta_{i(max)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.95</td>
<td>440000</td>
<td>63</td>
<td>340500</td>
<td>63</td>
<td>1.0</td>
</tr>
<tr>
<td>0.95</td>
<td>440000</td>
<td>63</td>
<td>392000</td>
<td>62</td>
<td>0.3</td>
</tr>
<tr>
<td>0.95</td>
<td>440000</td>
<td>63</td>
<td>411000</td>
<td>62</td>
<td>0.2</td>
</tr>
<tr>
<td>0.95</td>
<td>440000</td>
<td>63</td>
<td>430500</td>
<td>57</td>
<td>0.15</td>
</tr>
<tr>
<td>0.95</td>
<td>440000</td>
<td>63</td>
<td>----</td>
<td>----</td>
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<tr>
<td>0.9</td>
<td>422500</td>
<td>87</td>
<td>304500</td>
<td>87</td>
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<tr>
<td>0.9</td>
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<td>87</td>
<td>309500</td>
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</tr>
<tr>
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<tr>
<td>0.9</td>
<td>422500</td>
<td>87</td>
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<td>----</td>
<td>0.1</td>
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Similarly, the risk level of Part 2 may be deemed unacceptable to the decision maker. To rectify this, one more constraint is added to the above optimization process by way of adding a maximum acceptable stockout likelihood value, $\beta_{i(\text{max})}$. This means that however low impact a failure to meet a demand for a part is, a minimum stock level will be maintained. $\beta_{i(\text{max})}$ for the scenario with values as indicated in the first row of the Table is 1.0 i.e. there is no upper limit to the stockout likelihood. In the subsequent values, $\beta_{i(\text{max})}$ is changed to assess the impact on other parameters of interest.

As a contrast to the above scenario (indicated in the first row of the Table), Figures 3 and 4 show the results when $\alpha_{i(\text{ref})}=0.95$ and $\beta_{i(\text{max})}$ is 0.15 (scenario indicated in the fourth row of the Table). As shown, with an introduction of a constraint $\beta_{i(\text{max})}=0.15$, there is an increase in $TSV_o$ and a decrease in $TRV_o$. The increase in $TSV_o$ reflects the extra expense involved in maintaining a minimum level of inventory and the decrease in $TRV_o$ reflects the decreasing risk profile of spares as stock holding is made to increase consistent with smaller values of $\beta_{i(\text{max})}$.
In the Table, for some scenarios there is no optimal solution for the associated baseline TSV and TRV. This is indicated by ---- in the respective cells of the Table.

<table>
<thead>
<tr>
<th>Part 1: Establishing baseline values</th>
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<td>10</td>
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</table>

440000

<table>
<thead>
<tr>
<th>Part 2: Optimizing values</th>
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<tbody>
<tr>
<td>Table</td>
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</table>

440000

Max stock value acceptable: 440000
Max stockout acceptable time: \( \beta_{i(max)} \)

Figure 3: Model with maximum acceptable stockout constraint

The Table shows how the optimized values of TSV and TRV change when \( \beta_{i(max)} \) values are changed. To provide a better perspective, two values of \( \alpha_{i(ref)} \) have been used.
Figure 4: Risk Value of parts before and after Optimization

It is observed that as $\beta_{i(max)}$ decreases, there is an increase in $TSV_o$ and a general decrease in the $TRV_o$ values. $TSV_o$ values increase as a minimum level of inventory has been stipulated regardless of the risk profile of a part. $TRV_o$ values tend to decrease as the risk of stockout decreases. However, in one instance, shown by the highlighted row in the Table, somewhat counter intuitively and against the trend, the $TRV_o$ increases. This is probably due to the constraint in the linear optimization that the optimum number of parts should be an integer.

Figure 5: Effect of Beta on optimized individual Risk Values of parts in the Spares Inventory
Figure 5 above shows the impact of change in Beta values on individual optimized Risk Values of parts. Here, the model described above was run for four values of Beta i.e., 0.15, 0.20, 0.30 and 1.00. $\beta_{i(\text{max})}=0.15$ means that an expected stockout likelihood of up to 15% is acceptable; $\beta_{i(\text{max})}=1.00$ means that a total absence of stock of any spare is acceptable. The risk profiles of the ten parts (depicted by their Risk Values on the vertical axis) are shown. The horizontal axis depicts Part Number, the Consequence Value in brackets and the Cost Price of that part. For example, 1 (M) 1000, the first entry on the horizontal axis, stands for Part 1 with M Consequence Value and a Cost Price of 1000. For Part 1, the Risk Value reduces to zero as Beta increases. This is because the part is relatively of M consequence and cheap. With increase in Beta values, money is freed from elsewhere for this part to be stocked more. The same logic holds true for Part 2. Part 3 is expensive although of VL consequence. Hence an increase in Beta values raises its optimized Risk Value. Part 4 is accorded top priority as it is of VH consequence and is somewhat relatively cheaper. Part 5 is of VH consequence but because of its high cost cannot be stocked at the level of Part 4. Hence it has a Risk Value greater than that of Part 4 for different values of Beta. If one analyses other parts in Figure 5, the logic behind the methodology emerges.

This discussion shows how a decision maker can get various perspectives on the risk profile of the inventory by using this methodology. The model shown here returns a list of optimal number of units of spares to be held in an inventory such that i) the corresponding expenses are minimized ii) the overall risk profile of the system (the inventory) is less than the reference one and iii) the risk associated with individual parts is less than a specified value.
7.0 SOME LIMITATIONS AND FURTHER RESEARCH

The consequence or impact of a failure to meet a demand for a spare is a qualitative assessment in the model described above. It is worth noting that the same model will work by directly putting in the likely impact cost (in monetary terms) of a failure to meet a demand for a particular spare. However, it is at times difficult to quantify the full implications of such an event. Therefore, such qualitative assessments, despite the subjectivity involved, are often the best way to fully estimate the impact of an event. One can make such estimates more precise by fine tuning the consequences part of the risk estimate. For example, CoF (Consequence of Failure to meet a demand) can be a weighted sum of various consequences factor values such as: extra cost of procuring a part on an urgent basis and the lead time under such circumstances, availability of technical personnel to effect repairs, knock on effect of failure to meet a part on the general availability of the system and the risk of obsolescence of a part or the machine itself. The Appendix shows how such an approach can be developed. The approach consists of the following main steps: (1) Identify factors that impinge on a failure to meet a demand for a spare- impact factors (IF) - for each spare under consideration. In the table in the Appendix, these are lead time, availability of technical staff, knock-on failures and associated demands, potential for machine or spare redundancy and obsolescence (2) Ascribe weights to each of these impact factors to reflect their relative importance. In the table, these are 10, 10, 60, 15, and 5 for IF1 through to IF5 respectively. (3) Determine relative importance values for VH, H, M, L or VL representing Very High, High, Medium, Low and Very Low. These are shown to be 100, 80, 60, 40 and 20 respectively. (4) The spare is then assessed qualitatively- VH, H, M, L or VL - under each of the impact factors identified in step (1). The net result of this exercise is an aggregate Impact Value. This is ‘84’ in the example shown in the Appendix. This process is repeated for each spare that is
under consideration in an inventory. The relative weights or values in step (2) and step (3) may or may not be the same for all parts. Indeed, impact factors also may differ with parts.

This model takes an expected demand for a period as given; the model in its current form is thus based on periodic reviews. The forecast can be made continuous by using a moving average method for the demand trend which can make this a continuous review model that may be more advantageous in some circumstances. The model can also be configured to take in probabilistic distributions as demand forecast. A more advanced version of this model is being developed along these lines.

More work needs to be done to show how the approach shown here can be used in conjunction with more conventional ones such as the Economic Order Quantity (EOR) and the Materials Requirement planning (MRP) approaches.

Attempts are underway to implement this methodology and present a case study.

### 8.0 CONCLUSIONS

This paper applies risk based principles to spares inventory management. It extends the risk based approach that is well established in other areas of industry and used for planning activities such as maintenance and inspection within process industry. Based on the risk profile of each part, the model shown here presents the most optimal combination of spares to be held in an inventory such that the cost of holding such an inventory is minimized subject to a stipulated maximum individual risk of a stockout of a part and an overall risk of stockout within a system. The approach outlined here has the potential to increase plant or system availability and manage business as well as operational risks. It is thus of interest to a number of industry stakeholders including operators, maintenance personnel, regulators and insurance companies.
9.0 ACKNOWLEDGEMENTS

This research has been funded by the Centre for Innovative and Collaborative Engineering (CICE) at Loughborough University, UK in collaboration with TWI Ltd at Cambridge, UK via the Engineering Doctorate (EngD) scheme. Inspiration for developing this methodology came from a real life problem in the shipping sector brought to the notice of the lead author, courtesy of Lloyd’s Register, London, UK.

REFERENCES

(2) API: Risk-based Inspection, Recommended Practice 580, 2002, American Petroleum Institute, USA
(3) API: Risk Based Inspection, Base Resource Document, 2000, 5-1-5-4, American Petroleum Institute, USA


APPENDIX

DERIVING CONSEQUENCE VALUE FOR A PART FROM A NUMBER OF CONSEQUENCE (IMPACT) FACTORS

<table>
<thead>
<tr>
<th>Impact Factors</th>
<th>IF1</th>
<th>IF2</th>
<th>IF3</th>
<th>IF4</th>
<th>IF5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Lead time</td>
<td>Tech</td>
<td>Staff</td>
<td>Knock on</td>
<td>Reliability</td>
<td>Obsolescence</td>
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<tr>
<td>Weights</td>
<td>10</td>
<td>10</td>
<td>60</td>
<td>15</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>Assessment</td>
<td>H</td>
<td>M</td>
<td>VH</td>
<td>L</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>6</td>
<td>60</td>
<td>6</td>
<td>4</td>
<td>84</td>
</tr>
</tbody>
</table>

Where,

the value ‘8’ in the first column is

\[(10 \times 80)/100\]

Weights need to total 100 as this is a relative assessment

The weighted total ‘84’ is the CoF value for that part
APPENDIX C : PAPER 3

OPTIMISATION OF RESOURCES FOR MANAGING COMPETING RISKS

Ujjwal R Bharadwaj*

John B Wintle; V V Silberschmidt; John D Andrews

The model for managing risk presented in this paper was developed to address the problem of how many parts of different kinds of a major industrial enterprise should advance in order for stock to operate at optimum efficiency given that failures may occur in service. The particular application was a fleet of cargo ships where parts of different kinds are required to keep ships available for service. For example, spare propellers are expensive items to hold in stock, but the consequential costs of not having a spare when required can also be expensive. There is an optimum number of propellers that it is worth holding in order to balance the cost of stocking too many against the risk of a stock-out. Such risk optimization techniques, in general, find the optimum trade-off between the cost of a risk mitigating measure and the expected value of risk without that measure. They have the potential of being applied more widely within structural integrity and asset management, in any situation where competing risks need to be managed within finite resources. They may therefore find application in areas such as risk based inspection and more generally in other areas of risk management.
INTRODUCTION

The level of spares in an inventory has a direct bearing on machine availability. The availability of a machine is a function of the mean time to correct a failure which in turn depends upon, among other factors, the time to obtain a spare (to conduct repairs) or a replacement. The level of spares in a spares inventory is constrained by the cost of holding stock and the penalty of being out of stock. In a competitive climate companies strive to keep their spares inventory at an optimum level to minimize the costs involved. This paper presents a new approach - a risk based approach - to spares inventory management aimed at establishing an optimum level of spares such that financial benefit is maximized within accepted levels of risk, and the remaining (residual) risks are clearly identified. The paper presents a framework that enables consistent and auditable decision making in spares inventory management.

Risk based approaches are used in many sectors of industry and for prioritizing different types of actions; for example, there are risk based approaches in the process industry to manage maintenance and inspection and there are standards or guidance documents to implement these approaches (ASME [1], API [2], API [3] and EEMUA [4]). As opposed to other approaches, in a risk based approach, actions are based on the risk estimate of various options. In the current context, this means maintaining an inventory at an optimal level depending on the risk profile of the spares in which the likelihood of a failure to meet the demand for a spare is considered in conjunction with the consequences of the failure to meet
that demand. The optimal level is such that financial benefits are optimized given risk associated constraints.

The paper discusses some of the unique features of spares inventories vis-à-vis other types of inventories. There is also a section on typical costs associated with inventories followed by a brief note on the main principles underlying various current approaches to spares inventory management. The main body of the paper then presents the risk based methodology and the basic model that has been created to implement that methodology. This is followed by possible areas of further research and conclusions.

**SPARE PARTS INVENTORIES**

Spare parts inventories are maintenance inventories; they are used by maintenance personnel to keep machines available and exist to meet an internal demand for spares. They perform a different function compared to other inventories such as Work-in-progress (WIP) inventories and Finished Product Inventories. WIP inventories smooth out irregularities in production flow. These irregularities are caused by factors such as changes in product mix, equipment breakdowns, differences in production rates, between processes and material handling. Finished Product Inventories provide a buffer stock to protect against lead time demand, differences in quality levels, differences in machine production rates, labor troubles, scheduling problems, gap between capacity and demand and other well established production problems, Kennedy [5].

Characteristics of spare parts inventories: Spares inventories are hugely influenced by maintenance policies rather than customer usages that dictate WIP or Finished Product Inventories. For scheduled maintenance, the demand for spares is relatively more predictable
and it may be possible to order parts to arrive just in time for use and indeed not stock such parts at all. For unplanned maintenance, a lack of some safety stock often means that the consequences of not keeping some safety stock include production loss. There are other factors such as the amount of redundancy within a system, availability of reliability information from condition monitoring equipment, dependency of failure events, possibility of demands being met by cannibalism and the effect of parts or machine obsolescence on the level of stock holding. There has also been research illustrating how other factors such as the organizational context of inventories, especially the responsibilities and authorities of the persons concerned, have a bearing on inventory management, Zomerdijk and Jan [6].

SOME TYPICAL COSTS ASSOCIATED WITH INVENTORIES

Ordering and setting up costs: These are fixed costs that do not depend on the size of the order. For example, ordering costs would include paperwork and billing associated with the order. For parts made in-house, ordering and set up costs would include the cost of labor, setting up and shutting down the associated machinery.

Unit purchasing cost: This is the variable unit cost of a part or a component. If the part is manufactured in-house, it includes the variable labor cost, the overhead cost, and the raw material cost needed to produce a single unit. If this part is ordered from an external source, then the unit purchase cost must include the shipping cost.

Holding or carrying cost: These are essentially the inventory costs expressed in monetary value per unit part per year. It includes storage cost, insurance cost, taxes on inventory, and cost due to the possibility of spoilage, theft, or obsolescence. However, usually the most significant of the holding cost is the opportunity cost incurred by tying up capital in inventory.
The opportunity cost is the return the company would expect on an investment elsewhere rather than in stock-holding.

Stockout costs: When a demand for a product or a part is not met on time, a stockout is said to have occurred. If it is acceptable for demands to be met at a later date, no matter how much later, it is said that demands may be back-ordered. In the current context, risk is the combination of the probability of a stockout event and its consequence, where a stockout is an event in which a spare is not available on demand. If it is necessary for demands to be met on time, and if this is not achieved, then the scenario is a lost case one. In the current context, a lost case may result in production loss, regulatory penalty and other consequences such as loss of goodwill. Usually it is more difficult to measure the cost of a stockout rather than ordering, purchasing or holding costs.

APPROACHES TO INVENTORY MANAGEMENT

There are different approaches to Inventory Management. Prasad [7] categorizes inventory models into two: Economic Order Quantity (EOQ) and Materials Requirement Planning (MRP). Under these, he classifies about ninety inventory models. The basic model in an EOR method determines, subject to a number of assumptions, an ordering policy that minimizes the yearly sum of ordering cost, purchasing cost, and the holding cost of a part in the inventory. The basic model in an MRP based method considers the relationship between a component that is demanded and other associated (sub) components that also need to be available in order to fulfill that demand.

Winston [8] classifies models as Deterministic EOQ Models, Probabilistic Models and other recent models such as MRP, Just-in-time (JIT) and Exchange Curves. Nahmias [9]
looks specifically at repairable inventory systems and classifies existing models into three
general classes: continuous review, periodic review and models based on cyclic queuing
systems. The Risk Based approach presented here is unique in that it does not completely fall
in any of these categories although it might have some elements of the approaches listed
above.

THE RISK BASED APPROACH TO SPARE PARTS INVENTORY MANAGEMENT

In the current context, the following terms have a special meaning: Risk is the combination of
the probability of a stock out event and its consequence where a stockout is an event when a
spare is not available on demand. Qualitative Risk Analysis broadly covers methods that use
engineering judgment and experience as the bases for the analysis of probabilities and
consequences of failure. Failure Modes, Effects, and Criticality Analysis (FMECA) and
Hazard and Operability Studies (HAZOPs) are examples of qualitative risk analysis that
become quantitative risk analysis when consequences and failure probability values are
estimated. Quantitative Risk Analysis a) identifies and delineates the combinations of events
that, if they occur lead to an undesired event b) estimates the frequency of occurrence for each
combination c) estimates the consequences. The approach shown here is a semi-quantitative
approach that captures best estimates from experts as well as raw historical data. The risk
referred here is relative risk which is a comparative risk of components or equipment in
relation to each other.

In the method described below, a risk profile of the spares is obtained by considering the
likelihood of a failure to meet the demand for a spare in conjunction with the consequences of
the failure to meet that demand. This risk profile is then used to find the optimal level of
inventory such that financial benefit is maximized given an identified acceptable risk level.
A BASIC MODEL TO IMPLEMENT THE APPROACH

Underlying concepts

The model has two parts: Part 1 establishes baseline values, and Part 2 optimizes values. The implementation of the approach is shown by way of an example shown in Figure 1.

Part 1: Obtaining baseline values:

This part of the model aims at establishing baseline values for certain parameters for the purpose of optimizing in the second part of the model. The parameters with their descriptions are as follows:

\[ i \text{ = unique part number for identification; } \]

\[ n_{i{(\text{max})}} = \text{Expected maximum number of spares required in a planning period, based on historical data, expert opinion, generic data or a mix of these. There are guidelines/procedures for combining data from various sources (Clemen and Winkler [10], ASME [11]).} \]

\[ \alpha_i = \text{ratio of part } i \text{ in stock to the expected demand depending on } \alpha_{i{(\text{ref})}}; \]

\[ \alpha_{i{(\text{ref})}} = \text{reference (baseline) value of } \alpha_i \text{ for planning purpose (to obtain baseline values)}; \]

\[ n_i = \alpha_{i{(\text{ref})}} \times F_i = \text{number of parts held in stock, rounded to the nearest integer;} \]

\[ C_i = \text{net unit cost of part } i; \]

\[ \text{CoF}_i = \text{consequence of a stockout for part } i; \]
\( \beta_i = \) Stockout frequency estimate for part \( i \), assuming stock outs are proportional to stock levels

\[
1 - \frac{n_i}{n_i(\text{max})} = P(x_i) = P(n_i < x_i \leq n_i(\text{max}))
\]

(1)

where \( P(x_i) \) = the probability of a stockout given that a) a quantity \( x_i \) of that part may be required during the timeframe i.e. demand for that part b) \( n_i \) is the quantity in stock c) \( n_i(\text{max}) \) being the maximum expected requirement of part \( i \); this is assuming that the demand for spares follows a uniform distribution.

\( RV_i = \) Risk value associated with part \( i \)

\[
RV_i = (\text{Quantified } CoF_i) \times \beta_i
\]

(2)

\( TSV = \sum n_i \times C_i \)

(3)

\( TRV = \sum RV_i \)

(4)

In the model shown above, qualitative estimates of \( CoF_i \), VH, H, M, L, VL have been assigned values 100, 80, 60, 40 and 20 respectively. In a more advanced model, these values would be a weighted average of values obtained by considering a number of consequence or impact factors. One such possible scheme is shown in the Figure 5.

**Part 2: Obtaining optimized values:**

This part of the model contains optimized values obtained after using a linear optimizing tool using the values in Part 1 of the model, wherever applicable. The optimized values contain the subscript ‘o’. For example, \( n_{io} \) is the optimized value of units of part \( i \) to be held in the inventory.
Working of the model:

At the outset, in Part 1 of the model, an appropriate value for $\alpha_{i(\text{ref})}$ is assumed; in Figure 1, this is 0.90. $\alpha_{i(\text{ref})}$ (shown in the highlighted box with a small circle towards its top right corner) is a percentage of the expected spare parts demand, necessitated by failures, to be held in the inventory. This starting assumption is necessary to find baseline values for Total Stock Value (TSV) and the Total Risk Value (TRV) of the inventory, say, $TSV_b$ and $TRV_b$ respectively where,

$$TSV_b = \sum n_i \cdot C_i$$  \hspace{1cm} (5)

$$TRV_b = \sum RV_i$$  \hspace{1cm} (6)

The values above are, in essence, baseline or reference values that establish what is an acceptable level of overall risk and the associated cost of stock holding at that level. Having established these baseline values as a starting point, we then move on to Part 2 of the model in which linear optimization is carried out. In the model demonstrated here, the Linear Programming is through the Solver add-in to Microsoft Excel.

The optimization here is as follows:

Minimize $TSV$ such that $TRV \leq TRV_b$. All values are integers and greater than zero. The optimized values for TSV and TRV are $TSV_o$ and $TRV_o$ respectively.

Figure 1 shows the risk profile of various components in the last column. The figure shows Stockout Risk values associated with $\alpha_{i(\text{ref})} = 0.90$ both before and after optimization.

Modes of operation:

(A) Minimize Total Risk
Figure 1 shows the results when Total Risk is minimized subject to given budget. As seen the Total Risk Value reduces from 87 before optimization to 16 after optimization.

(B) Minimize Total Cost

Figure 2 shows the results when Total (inventory) Cost is minimized subject to a reference level of (tolerable) Total Risk. As shown in the figure, the Total Cost comes down to 304500 from 422500, given a Total Risk Value tolerance of 87.

Although optimization has been carried out as described, there may be some components for which the risk profile may be considered too high to be acceptable to the decision maker. For example, as shown in Figure 1, the RV for part 3 i.e. $RV_3$ is 16; this is an expensive part of VL consequence, but the likelihood value of a stockout relative to other parts is high at $\beta_3 = 0.8$. Similarly, in Figure 2, Part 3 has a Stockout likelihood of 1.00 (100%). Such a value may be deemed too high by the decision maker especially when it is substantially different to that implied by $\alpha_i(\text{ref})$ that was assumed initially in Part 1 of the model as part of establishing baseline values. It may be noted here that $\alpha_i(\text{ref}) = 0.9$ implies a reference stock level that expects to meet 90% of the expected maximum demand, i.e., other things being equal, 10% of expected maximum demand is expected not to be met: stockout would be at 10%.

(C) Minimize Total Risk or Total Cost subject to maximum Individual Risk constraints

To rectify this, one more constraint is added to the above optimization process by way of adding a maximum acceptable stockout likelihood value for each of the parts, $\beta_i(\text{max})$. This constraint is shown in the highlighted box with two concentric circles towards its top right corner in Figure 3. In Figures 1 and 2, $\beta_i(\text{max})$ is mentioned but the value is 1.0 so that, in
effect, it is not a constraint. Imposing $\beta_{i(\text{max})}$ constraint means that however low impact a failure to meet a demand for a part is, a minimum stock level will be maintained. Figures 3 and 4 repeat the optimisation with same values as in Figures 1 and 2 with the added constraint of $\beta_{i(\text{max})} = 0.3$. As seen in Figures 3 and 4, the additional constraint ensures that however Low consequence a part maybe and however expensive it may be, it will be stocked within the stipulated level (0.7 or 70% of expected maximum demand, in this case) of tolerable Risk both at a system level (Total Risk Value) and at the individual or component level as indicated by the various $\beta_{\text{io}}$ values. However, as shown in the Figures, this extra risk mitigation effected by the constraint $\beta_{i(\text{max})}$ comes at a price. Figures 3 and 4 show that the Optimised Total Risk value is now 32 up from 16, and the Optimised Total Cost is 375500 up from 304500.

**FURTHER RESEARCH**

The consequence or impact of a failure to meet a demand for a spare is a qualitative assessment in the model described above. It is worth noting that the same model will work by directly putting in the likely impact cost (in monetary terms) of a failure to meet a demand for a particular spare. However, it is at times difficult to quantify the full implications of such an event. Therefore, such qualitative assessments, despite the subjectivity involved, are often the best way to fully estimate the impact of an event. One can make such estimates more precise by fine tuning the consequences part of the risk estimate. For example, CoF (Consequence of Failure to meet a demand i.e., a stockout) can be a weighted sum of various consequences factor values such as: extra cost of procuring a part on an urgent basis and the lead time under such circumstances, availability of technical personnel to effect repairs, knock on effect of
failure to meet a part on the general availability of the system and the risk of obsolescence of
a part or the machine itself. Figure 6 shows how such an approach can be developed. The
approach consists of the following main steps: (1) Identify factors that impinge on a failure to
meet a demand for a spare- impact factors (IF) - for each spare under consideration. In Figure
6, these are lead time, availability of technical staff, knock-on failures and associated
demands, potential for machine or spare redundancy and obsolescence (2) Ascribe weights to
each of these impact factors to reflect their relative importance. In the table, these are 10, 10,
60, 15, and 5 for IF1 through to IF5 respectively. (3) Determine relative importance values for
VH, H, M, L or VL representing Very High, High, Medium, Low and Very Low. These are
shown to be 100, 80, 60, 40 and 20 respectively. (4) The spare is then assessed qualitatively-
VH, H, M, L or VL - under each of the impact factors identified in step (1). The net result of
this exercise is an aggregate Impact Value. This is ‘84’ in the example shown in the Figure 5.
This process is repeated for each spare that is under consideration in an inventory. The
relative weights or values in step (2) and step (3) may or may not be the same for all parts.
Indeed, impact factors also may differ with parts.

This model takes an expected maximum demand for a period as given; the model in its
current form is thus based on periodic reviews. The forecast can be made continuous by using
a moving average method for the demand trend which can make this a continuous review
model that may be more advantageous in some circumstances. The model can also be
configured to take in probabilistic distributions as demand forecast. A more advanced version
of this model is being developed along these lines.
CONCLUSIONS

This paper applies risk based principles to spares inventory management. It extends the risk based approach that is well established in other areas of industry. The example illustrates a technique of managing risk within user specified constraints as applicable to Spares Inventory. Risks can be minimized subject to a given Budget (Maximum Total Cost), and Total Costs can be minimized subject to a specified tolerable level of Risk. The optimisation can be done at a system level (Total Cost and Total Risk) and it can be done at a component level too, thus affording the user to manage risks at different levels.

The approach outlined here has the potential to increase plant or system availability and manage business as well as operational risks. It is thus of interest to a number of industry stakeholders including operators, maintenance personnel, regulators and insurance companies. The methodology can be used in other areas that impinge on the structural integrity and asset management such as Inspection and Maintenance where competing risks (of failure) need to be managed within finite resources.

ACKNOWLEDGEMENTS

This research has been funded by the Centre for Innovative and Collaborative Engineering (CICE) at Loughborough University, UK in collaboration with TWI Ltd at Cambridge, UK via the Engineering Doctorate (EngD) scheme. Inspiration for developing this methodology came from a real life problem in the shipping sector brought to the notice of the lead author, courtesy of Lloyd’s Register, London, UK.
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(3) API: Risk-based Inspection, Recommended Practice 580, 2002, American Petroleum Institute, USA


### FIGURES

**Part 1: Establishing baseline values**

<table>
<thead>
<tr>
<th>Part no.</th>
<th>Expected Demand</th>
<th>Units in stock</th>
<th>Stock ratio</th>
<th>Unit cost</th>
<th>Stock value</th>
<th>Stockout consequence</th>
<th>Stockout freq est</th>
<th>Stockout Risk value</th>
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Minimize Total Risk subject to given Budget

---

**Part 2: Optimising values**

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Max stock value acceptable: 42500
Max stockout acceptable (allowance): 42500

Condition: (binary) always more than in equal to 1 (incl. 0).

Minimize Total Risk within Budget

Minimize Total Cost subject to a Total Risk Value

---

**Figure 1: Minimize Total Risk subject to given Budget**
Part 1: Establishing baseline values

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Minimize Total Risk subject to a tolerable level of Total Risk

Figure 3: Minimize Total Risk subject to given Budget and individual Risk constraints \((\beta_{max})\)

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Figure 4: Minimize Total Cost subject to a given tolerable level of Total Risk and individual Risk constraints ($\beta_i^{(\text{max})}$)

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<th>Impact Factors</th>
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Where, the value ‘8’ in the first column is (10*80)/100, weights need to total 100 as this is a relative assessment, the weighted total ‘84’ is the CoF value for that part.

Figure 5: Deriving Consequence Value for a part from a number of Consequence estimates
A RISK- BASED APPROACH TO ASSET INTEGRITY MANAGEMENT OF STRUCTURES AND EQUIPMENT

Bharadwaj, U.R., Silberschmidt, V.V., Wintle, J.B.

Abstract

Purpose

Inspection and maintenance of plant and machinery has traditionally been based on prescriptive industry practices. However, increased experience and a greater understanding of operational hazards is leading sections of industry to take a more informed approach to planning inspection and maintenance, targeting resources to reduce the risk to as low as reasonably practicable. The purpose of this paper is to present an approach to asset management to minimize risks in the most cost effective way.

Methodology

The methodology to implement the approach optimizes the decision-making for undertaking run-repair-replace decisions with the ultimate aim of maximising the Net Present Value (NPV) of the investment on such actions. The risk-based approach to asset integrity management, as opposed to the more conventional approaches, assesses failure in its wider context by considering not just the likelihood of failure, but also the consequences should the failure event occur.
Findings
The risk based presents a cost-effective way to minimise life cycle costs in the management of assets whilst maintaining reliability or availability targets, and operating within safety and environmental regulation.

Practical implications
In this paper, for demonstration, a wind turbine system consisting of a number of components including structural components is used. However, the methodology can be extended to any system in which components can be analyzed to provide the required inputs to the risk model.

Originality/ Value
At a time when competitive pressures force asset managers to prioritize their maintenance, the risk based methodology presented here is a rational, efficient and somewhat flexible way to asset integrity management.

Paper type
Research paper

Keywords: Risk management, Maintenance, Asset management, Life Cycle Management, Operations Management.
1. Introduction

Decisions within asset integrity management that include decisions regarding inspection, repair, maintenance and replacement have traditionally been based on a range of practices including the prescriptive time-based (rule-based) approach, the condition-based approach, Reliability Centred Maintenance (RCM) and Reactive Maintenance (RM).

Whilst there will remain the need for traditional approaches to asset integrity management, it is increasingly felt that more advanced approaches are required to reflect the complexity and innovation involved in the assets, and to operate at an optimal level within the competitive pressures faced by asset managers. Risk based approaches, as opposed to many other approaches, give operators some flexibility in the management of their assets whilst meeting the same objectives. The flexibility is as a result of undertaking actions not on a fixed schedule or rule, but on some identified measures of risk. The risk based approach uses risk based criteria to prioritize efforts and make the optimum use of this flexibility.

The uptake of risk based practices is growing as increased operational experience and a greater understanding of failures (and its consequences) lead some parts of industry to adopt a more informed approach to planning, targeting resources to reduce risk to as low as reasonably practicable. Risk based approaches are used in many sectors of industry and for prioritizing different types of actions; for example, there are risk based approaches in the process industry to manage maintenance and inspection and there are standards or guidance documents to implement these approaches (ASME, 2003; API, 2000; API, 2002; EEMUA, 2006).
This paper develops and demonstrates a risk-based methodology to estimate the optimum time of replacement or repair of a structure, in a system comprising a number of components, within constraints of the budget available, such that financial benefit of the action taken is maximised.

The paper starts with a discussion on risk and its analysis as applied to asset integrity management in general, and moves on to the concept of risk measured in terms of expected values, the concept of NPV, and the trade-off involved in risk-based decision-making within the constraints that apply.

2. The Risk Based Approach to asset integrity management

Risk

Risk has numerous definitions. Risk is a combination of the probability of an event and its consequence (API, 2002). It is a deviation from the normal or expected. Numerically, it is a product of probability of an event occurring and the consequence of the event.

A risk-based approach considers failure taking cognizance of the two elements that constitute risk - the probability (or likelihood) of failure and the consequence of that failure.

In the context of this paper, risk will involve the probability or the likelihood of failure of a component or a system of components to fulfil its design purpose in a given time frame and under given operating conditions. Where the two components of risk i.e. the likelihood and the consequence of a failure event are quantitatively expressed, risk will be expressed in terms of ‘expected loss’. Expected loss can be defined quantitatively as the product of the consequences (C) of a specific incident and the probability (P) over a time period or frequency of its occurrence (Andrews and Moss, 2002):
Risk Analysis methods

Risk analysis methods are generally categorised as qualitative or quantitative. There may be an intermediate category (semi-quantitative) depending upon how quantitative the risk analysis is. The API’s Recommended Practice 580 (API, 2002) on risk-based inspection describes a ‘continuum of approaches’ ranging from the qualitative to quantitative. The level of detail in risk analysis corresponding to a purely qualitative approach, on one end of the spectrum, is low compared to the purely quantitative one on the other. There are intermediate approaches that may have both qualitative and quantitative attributes.

Qualitative Analysis

Engineering judgment and experience are the basis for risk assessment in a qualitative analysis. The results of the analysis largely depend on the expertise of the user. The primary advantage of qualitative risk analysis is that it enables assessment in the absence of detailed (and entailing the use of substantial resources) numerical data. It is also the first pragmatic step to conduct a quantitative risk analysis by screening out components of less concern, and is often the best way to take a system-wide view. However, it is not a very detailed method and provides only a broad categorization of risk. Failure Modes, Effects and Criticality Analysis (FMECA) (MIL-STD-1629, 1980), Hazard and Operability Studies (HAZOPS), and the Risk Matrix approach are
examples of qualitative methods. In the Risk Matrix, approach, the likelihoods and consequences of failure are qualitatively described in broad ranges (e.g. high, medium or low).

**Quantitative Analysis**

Qualitative risk assessments become less discerning when the system complexity increases. So a quantitative method is often required to achieve risk discrimination of a system of components. Quantitative Analysis assigns numerical values to the probability (e.g. $10^{-5}$ failure events per year) and the consequences of failure (e.g. revenue loss or inventory released over 1,000 m$^2$). Qualitative Analysis techniques such as FMECA and HAZOPS can become quantitative when the values of failure consequence and failure probability are numerically estimated. This can be performed using a variety of references such as generic failure databases, elicited expert opinions, or calculated by means of specific engineering and statistical analysis (ASME, 2003). There are statistical methods for combining data from various sources or updating data with additional information, (Jordan, 2005), (Kallen and Noortwijk, 2005), (Thodi et. Al., 2009).

In the current discussion, it is assumed that there is a system comprising a number of structures and a qualitative analysis has identified high-risk components. For the sake of demonstration, consider the system as a wind turbine (comprising of electrical and structural components). Among high-risk components- the wind turbine tower structure- has been identified. For simplicity, wind turbine tower structure will be referred to as ‘structure’ in the discussion below. The paper now describes a methodology for performing quantitative analysis on the structure that has been identified as high risk and how the results of this analysis feeds into the planning/
decision-making in integrity management of the system. Again, for the sake of simplicity, the decisions involved are run or replace. However, the same method can be extended to other plan other actions in asset integrity management such as repair and inspection.

For the quantitative risk analysis method described in this paper, a failure frequency-time curve is developed by engineering analysis of the structure for the active or potentially active in-service damage mechanisms. Among the expected damage mechanisms, corrosion is chosen to demonstrate the methodology. The consequence of failure is in financial terms as it is assumed that the functioning of the structure is business-critical.

**Quantitative consequence analysis**

A possible scheme for quantitative assessment of consequences using FMEA is shown in Table 1. The table is for illustration only. There may be some intangibles remaining or if quantified, may be approximate assessments; for example, ‘technology confidence loss’ may be quantified in some way- losing similar projects or a drop in the share value of the company.

In the analysis that follows, for simplicity, the consequence considered and quantified is just the production loss.

3. **Quantitative probabilistic damage mechanism model for failure due to corrosion**

This paper does not discuss the details of damage models for use in probabilistic analysis. Instead it illustrates a simple probabilistic damage mechanism model for general corrosion of the tower structure. Consider a structure subject to corrosion. For the sake of simplicity, assume that this is
the only damage mechanism causing failure of the structure and that there is a breakdown of coating. The remaining life (RL) of the structure can be calculated as:

\[
RL = \frac{(Tc - MAT)}{CR}
\]  

(2)

Table 1: Identified consequences and associated costs of damage to a wind turbine tower

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Effect</th>
<th>Consequence category</th>
<th>Consequence</th>
<th>Cost (£k)</th>
<th>Source/comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion - Uniform Band in Splash Zone</td>
<td>Collapse</td>
<td>Production loss</td>
<td>Maintenance duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Secondary Damage</td>
<td>Other turbines</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Personal</td>
<td>Injury</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maintenance costs</td>
<td>Installation of new structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reputation</td>
<td>Insurance premium</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Repair</td>
<td>Technology confidence loss</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Find and Assess</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Repair</td>
<td>Cost production</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keep in service</td>
<td>Maintenance cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue - Circumferential cracking</td>
<td>Collapse</td>
<td>Production loss</td>
<td>Maintenance duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Secondary Damage</td>
<td>Other turbines</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Personal</td>
<td>Injury</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maintenance costs</td>
<td>Installation of new structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reputation</td>
<td>Insurance premium</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Repair</td>
<td>Technology confidence loss</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Find and Assess</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Repair</td>
<td>Cost production</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keep in service</td>
<td>Maintenance cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scouring</td>
<td>Collapse</td>
<td>Production loss</td>
<td>Maintenance duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Secondary Damage</td>
<td>Other turbines</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Personal</td>
<td>Injury</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maintenance costs</td>
<td>Installation of new structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reputation</td>
<td>Repair and recommission</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Repair</td>
<td>Technology confidence loss</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Find and Assess</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Repair</td>
<td>Cost production</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keep in service</td>
<td>Maintenance cost</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where, RL = remaining life (years); Tc = current thickness of the structure (mm);

MAT = minimum allowable thickness to maintain integrity of the structure (mm); and

CR = corrosion rate (mm/year). These terms are explained in more detail later in this section.

If To is the original nominal thickness of the structure, then at the end of t years,

\[
Tc = To - CR \times t.
\]  

(3)
The reliability of an element of a system can be determined based on a performance function that can be expressed in terms of basic random variables \((X_i)\) for relevant random loads and structural strength (Ayyub, 2003).

Mathematically, the performance function \(Z\) can be described as

\[
Z = (X_1, X_2, ..., X_n) = R - L
\]  \hspace{1cm} (4)

where, \(R\) is the resistance or strength and \(L\) is the load.

The limit state can be defined as

\[
Z \leq 0\hspace{1cm} (5)
\]

Accordingly, when \(Z < 0\), the element is in the failure state, and, when \(Z > 0\), it is in the survival state.

The limit state equation implied in equation (3.2), when remaining life is zero, can be expressed as

\[
RL = \frac{(T_c - MAT)}{CR} = \frac{(T_o - CR \times t - MAT)}{CR} = 0,
\]

\[
T_o - CR \times t - MAT = 0, \hspace{1cm} \text{which can be re-arranged to}
\]

\[
[T_o - MAT] - [CR \times t] = 0. \hspace{1cm} (6)
\]
where, the first term represents structural strength (R), and the second, load effect (L).

A purely deterministic RL model would have each independent variable in equation (2) as a specific value. This assumes that these variables have no random or probabilistic aspects but can be defined in a fixed predictable fashion. In reality, there is considerable uncertainty associated with these variables and each can be defined by a statistical distribution of values.

The corrosion rate (CR) maybe derived from periodic in-service measurements of metal loss resulting from corrosion or from laboratory tests. In the calculations that follow, CR is assumed to be a normal distribution with a mean of 0.4mm/year and a standard deviation of 0.1mm/year, N (0.4, 0.1). These values are for demonstration only. As CR cannot be negative, the distribution is truncated to so that the lower boundary is greater than or equal to zero.

The RL model has been created using the ‘@Risk’ software from Palisade Corporation. Figure 1 depicts the distribution for CR using the @Risk software. Numbers on the horizontal axis represent the corrosion rate in mm/year. (The percentage values on the horizontal axis show what percentage lie in a given range of values- this is not used in the below. The values on the vertical axis in figure 1 are also not used in the calculation below.) The distribution can also be obtained from fitting a curve to real values of CR as measured over a period of time and could well be a different kind of distribution.
Figure 1: Corrosion rate (mm/year) distribution

Current thickness ($T_c$) is known from the most recent thickness measurements on the structure, say during the year of assessment. If recent thickness measurements are not available, $T_c$ can be assumed to be equal to the original nominal thickness of the structure ($T_o$) as specified by the designer including tolerances, corrosion allowance, etc, and the RL calculated from the year of installation. For the purpose of demonstration, in the model, $T_o$ is also a normal distribution, $N(100, 1)$ i.e. with mean=100mm and standard deviation=1mm.

MAT is the absolute minimum allowable thickness calculated by the designer to prevent failure by overload, collapse, etc as appropriate. In the illustration this value is 90 mm. ‘Failure’ in this context is not having the minimum allowable design thickness (MAT) rather than actual physical collapse of the structure. The probability of not meeting MAT is greater than that of structural
collapse as there is a factor of safety within the minimum design thickness, making the analysis conservative.

In the method here, the statistical analysis tool - Palisade’s @RISK for Microsoft Excel is used to describe all the independent variables probabilistically, and RL is then calculated using Monte Carlo Simulation (MCS) technique. In this way, the calculated RL by MCS is actually a distribution of values, so that the annual probability of failure (the failure rate per year) over time can be obtained. This annual probability of failure, in the current context, is effectively the proportion of surviving population of structures from the previous year that is expected to fail within the year under consideration.

Annual probability of failure \( P(\text{RL} \leq 0) \) \hspace{1cm} (7)

For example, see figure 2 that shows an assessment of the annual probability of failure of a tower structure with (1) an initial (in the year of installation i.e. 2000) thickness of 100 mm with some deviation described by \( \text{N}(100,1) \); (2) Expected CR as \( \text{N}(0.4, 0.1) \) with negative values truncated; (3) MAT as 90 mm. The number of iterations is set to 1000. This means that for year 2000, 1000 values for CR and Tstart are selected from the respective stipulated distributions. These initial values are used in calculations for the year 2000 and all the subsequent years.
Figure 2: Screenshot of inputs and outputs of the corrosion model

For every year, equation (2) is used to calculate the annual probability of failures. For example, in the year 2013,

\[ T_{\text{start}} = 94.8 = T_c, \]  
where 94.8 in effect represents the mean of 1000 iterations;

\[ T_c - \text{MAT} \]  
too has 1000 values.

<table>
<thead>
<tr>
<th>Year</th>
<th>T_{\text{start}}</th>
<th>CR</th>
<th>Tend</th>
<th>PoF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>%</td>
</tr>
<tr>
<td>2000</td>
<td>100.0</td>
<td>0.4</td>
<td>99.6</td>
<td>0.0</td>
</tr>
<tr>
<td>2001</td>
<td>99.6</td>
<td>0.4</td>
<td>99.2</td>
<td>0.0</td>
</tr>
<tr>
<td>2002</td>
<td>99.2</td>
<td>0.4</td>
<td>98.8</td>
<td>0.0</td>
</tr>
<tr>
<td>2003</td>
<td>98.8</td>
<td>0.4</td>
<td>98.4</td>
<td>0.0</td>
</tr>
<tr>
<td>2004</td>
<td>98.4</td>
<td>0.4</td>
<td>98.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2005</td>
<td>98.0</td>
<td>0.4</td>
<td>97.6</td>
<td>0.0</td>
</tr>
<tr>
<td>2006</td>
<td>97.6</td>
<td>0.4</td>
<td>97.2</td>
<td>0.0</td>
</tr>
<tr>
<td>2007</td>
<td>97.2</td>
<td>0.4</td>
<td>96.8</td>
<td>0.0</td>
</tr>
<tr>
<td>2008</td>
<td>96.8</td>
<td>0.4</td>
<td>96.4</td>
<td>0.0</td>
</tr>
<tr>
<td>2009</td>
<td>96.4</td>
<td>0.4</td>
<td>96.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2010</td>
<td>96.0</td>
<td>0.4</td>
<td>95.6</td>
<td>0.0</td>
</tr>
<tr>
<td>2011</td>
<td>95.6</td>
<td>0.4</td>
<td>95.2</td>
<td>0.0</td>
</tr>
<tr>
<td>2012</td>
<td>95.2</td>
<td>0.4</td>
<td>94.8</td>
<td>0.1</td>
</tr>
<tr>
<td>2013</td>
<td>94.8</td>
<td>0.4</td>
<td>94.4</td>
<td>0.7</td>
</tr>
<tr>
<td>2014</td>
<td>94.4</td>
<td>0.4</td>
<td>94.0</td>
<td>1.1</td>
</tr>
<tr>
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<td>0.4</td>
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<td>2.2</td>
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<tr>
<td>2016</td>
<td>93.6</td>
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<td>93.2</td>
<td>5.6</td>
</tr>
<tr>
<td>2017</td>
<td>93.2</td>
<td>0.4</td>
<td>92.8</td>
<td>8.4</td>
</tr>
<tr>
<td>2018</td>
<td>92.8</td>
<td>0.4</td>
<td>92.4</td>
<td>13.3</td>
</tr>
<tr>
<td>2019</td>
<td>92.4</td>
<td>0.4</td>
<td>92.0</td>
<td>19.4</td>
</tr>
<tr>
<td>2020</td>
<td>92.0</td>
<td>0.4</td>
<td>91.6</td>
<td>25.6</td>
</tr>
<tr>
<td>2021</td>
<td>91.6</td>
<td>0.4</td>
<td>91.2</td>
<td>30.2</td>
</tr>
<tr>
<td>2022</td>
<td>91.2</td>
<td>0.4</td>
<td>90.8</td>
<td>36.1</td>
</tr>
<tr>
<td>2023</td>
<td>90.8</td>
<td>0.4</td>
<td>90.4</td>
<td>43.3</td>
</tr>
<tr>
<td>2024</td>
<td>90.4</td>
<td>0.4</td>
<td>90.0</td>
<td>50.7</td>
</tr>
<tr>
<td>2025</td>
<td>90.0</td>
<td>0.4</td>
<td>89.6</td>
<td>56.3</td>
</tr>
<tr>
<td>2026</td>
<td>89.6</td>
<td>0.4</td>
<td>89.2</td>
<td>61.6</td>
</tr>
</tbody>
</table>
The algorithm counts the number of times $T_c - MAT$ is negative or zero; in this case 7 times out of a total of 1000 iterations. These are the times when, as per equation (2), $RL \leq 0$. Percentage values give $P(RL \leq 0)$ as shown in column 5 in figure 2.

This annual probability of failure (failure rate) versus time curve is used in the next stage in which the timing of an action (repair/ replacement) can be optimised such that financial benefit is optimised.

Figure 3: The annual probability of failure versus time curve
4. Risk based financial optimisation of maintenance action given a failure trend

The need for financial criterion in maintenance decision making

Maintenance projects are increasingly being evaluated by decision makers who need to understand the implications of various options in financial terms. Although predictive maintenance techniques have matured, the predictions are in engineering terms. Thus, there is a need to express the effects of engineering wear and tear in financial terms. In the current context, this is done by evaluating the cost of the consequences of failure owing to wear and tear of plant and machinery.

The drivers for a consistent decision making methodology in maintenance

Many old plants, structures, capital equipment or components are in their Ageing period of life. However, increasing competition means many of them cannot be replaced and need to have their useful life extended. In addition, new components are often designed to operate with maximum efficiency, and are designed with lower “margins of error” against assumed operating conditions. Each action (or project) has costs associated with it. These costs are, in essence, investments made by the concerned asset owner with the expectation of certain return on the investment(s). The decision maker will normally be faced with a number of projects competing for such investments, and therefore needs to take decisions that maximise the returns on these investments within the constraints that apply (Tam and Price, 2008). The most widely understood financial techniques to evaluate projects include ‘return on investment’, ‘pay-back period’ and ‘discounted cash flow (DCC)’ methods (Brealey, Myers 1991). These techniques have various strengths and
weaknesses. The methodology here employs the net present value (NPV) technique that is a form of DCC analysis.

**NPV in financial analysis**

In the current discussion, it is assumed that a project with a higher NPV is a better investment than a project with a lower NPV. The NPV of a project is the present (current) value of the total future cash flows, i.e. the net of both positive (income) and negative (cost) cash flows. NPV considers the time value of money by discounting all the cash flows, and it is calculated as follows:

\[
NPV = \sum_{t=0}^{N} \left( \frac{C_t}{(1+r)^t} \right)
\]

\(N\) = project life (years); \(t\) = timing of cash flow (year); \(r\) = interest rate, or discount rate; and \(C_t\) = cash flow in year \(t\).

The future cash flows are ‘expected’ cash flows, as they do not occur with certainty. The uncertainty arises in the engineering analysis to calculate the probability of failure over time for the damage mechanism(s) of interest.

The risk associated with any project is expressed in terms of its NPV by using expected values (EV). The EV of a failure event is the product of the probability of an event occurring and the cost of consequence of that event. The probability of an event and the cost of the consequence(s) of that event is directly assessed from prior quantitative analyses; the consequence cost is expressed in financial terms.
Thus, the NPV of a project with uncertain outcomes is the sum of the expected values of all future discounted cash flows, as follows:

\[ NPV = \sum_{t=0}^{N} (p_t \times C_t) \times (1 + r)^t \]  

(9)

where, \( p_t \) = the probability of the event occurring at time \( t \).

**The risk-based optimisation model**

The optimisation maximises the NPV of the action (repair/replacement) under consideration. In this case, the optimisation finds the least negative value of NPV. Cash inflows are treated as positive and cash outflows as negative: 1) money spent on an action is negative, 2) failure consequence costs ((unplanned) outages due to failure mainly production loss considered here, for simplicity) is also negative, but 3) failure costs avoided by undertaking the action under consideration are considered positive.

Consider that our planning period is from \( t=0 \) to \( t=N \) and the year of assessment is \( t=0 \). Let us consider the NPV of an action undertaken in any year \( t=n \). It is given by:

\[ NPV = \text{(Expected present value of action undertaken in year } t=n) + \text{(Expected present value of costs due to outages prior to the action)} + \text{(Expected present value of costs due to outages avoided due the action)} \]  

(10)
The first two terms in equation (10) are negative, the third is positive.

Hence,

\[
NPV = \left\{ -\sum_{t=n}^{N} (C_{t} \times (1+r)^{t}) \right\} + \left\{ \sum_{t=0}^{n} (p_{t} \times C_{Bt} \times (1+r)^{t}) \right\} + \left\{ \sum_{t=n+1}^{N} (p_{t} \times C_{Bt} \times (1+r)^{t}) \right\}
\]

(11)

In equation (11), for the NPV of an action taken at time \(t=n\), the following can be defined:

\[
CB_{t} = \text{Cash flows associated with production in year } t;
\]

\[
CP_{t} = \text{Cash flows associated with implementing the project in year } t, \text{ including any tax credits (positive cash flow) on depreciation costs (Collier & Glagola, 1998)};
\]

\[
N = \text{the maintenance planner’s strategic planning period, i.e. from } t=0 \text{ to } t=N;
\]

\[
n = \text{year in which the action is proposed to be undertaken};
\]

\[
p_{t} = \text{probability of the event (failure leading to the particular consequence) occurring in year ‘}t’;
\]

and

\[
r = \text{interest rate, i.e. the cost of money (finance)}.
\]

The optimisation algorithm calculates the year of maintenance action for which the NPV is maximum (least negative, in this case), subject to stipulated constraints.
The maintenance action may be replacement or repair. In both cases, it is assumed that the cost of action includes the cost of initial problems (teething problems) and that once the equipment or structure is in place and functional, it begins its life cycle at a relatively very low failure rate.

The key inputs to the optimisation model are as follows:

(a) The annual probability of failure versus time values using which expected values are derived as per the formula discussed above; the failure trend is obtained from quantitative assessments.

(b) The consequence cost of failure (unplanned outage).

(c) Interest rates and depreciation as applicable.

(d) Any financial constraints, such as the annual maintenance budget limit.

(e) Although not shown in the calculations here, any non-financial constraints, e.g. those on failure rates due to safety regulations.

5. Demonstration of the model

The approach described above is demonstrated by evaluating three offshore wind turbine tower structures - structure 1, structure 2 and structure 3. The failure trend from a probabilistic corrosion model is presented in figures 2 (spreadsheet calculations) and 3 (graphical presentation). How the Action NPV (depicted by the curve with triangles) changes with the failure trend (curve with square boxes; the same curve as shown in figure 3) is shown figure 4. The values are obtained by using equations 10 and 11 for each year in the planning period.
The NPV of an action to mitigate the probability of failure over the operating life of a structure/equipment

<table>
<thead>
<tr>
<th>Probability of Failure %</th>
<th>Action NPV (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1020000</td>
</tr>
<tr>
<td></td>
<td>-1000000</td>
</tr>
<tr>
<td></td>
<td>-980000</td>
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<td>-960000</td>
</tr>
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<td>-880000</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>-840000</td>
</tr>
<tr>
<td></td>
<td>-820000</td>
</tr>
</tbody>
</table>

Figure 4: The optimum time of replacement of structure 1, given the cost of such action and the annual probability of failure over its operating life

The optimised replacement time for structure 1 - year 2016 - is shown in figure 4. This is the year in which the ‘Action NPV’ is the least negative.

The figure depicts the application of risk based approach to undertaking run-repair-replace decision-making for structure 1. The probability of failure versus time curve derived from remaining life estimates on its own is often incomplete information to the decision maker. The Action NPV versus time curve generated by the risk based approach enables one to make a more informed maintenance decision by considering the consequences of failure too. Thus the context
in which the structure is operating and the implications of it failing feed into the process of run-repair-replace decision-making.

The optimised action years for the other two structures are derived in the same way. This is shown in figure 5. It is seen that both structure 1 and structure 2 have the same year of replacement- 2016, and structure 3 has 2012 as the year of replacement. The figure shows a scenario in which the budget for repair/ replacement of structures in a wind farm is set to maximum of £ 6400,000 in any given year with an increase of 0.05 % every year. It is assumed that if this budget is not used in a given year on asset management actions within this wind farm, it is used elsewhere- there is no facility for a rollover. Due to this limit on expenses, if actions are taken as calculated, there would be deficits in the years in which the actions are taken.

To address this, optimisation is carried out again (using Solver in Microsoft Excel). The rescheduled time of action is shown in figure 6. All actions are now within the allocated budget. However, the change in schedule comes at a price: the NPV decreases from the previously optimised value of -£ 7118677 to -£ 7148132. To take the analyses one step further this loss in NPV could be compared to the expected cost of borrowing to see if actions can be taken in the years as originally identified as the most optimum time.

**In-service inspection optimisation**

The model could be extended to inspection actions. Instead of the replacement cost of the component, the cost of in-service inspection would be considered. Since such actions (projects) are usually accounted for as ‘expenses’ in the year in which they occur, rather than as
‘investments’ (which would then be written-off over several years), tax credits from depreciated costs do not arise. Since inspection costs are relatively low compared to production loss it is expected that the model would suggest the optimum year of inspection to be the first year of the planning period. To address this, to optimise in-service inspection dates:

1. Optimise the action date as if the action was replacement,
2. Inspect the equipment before this calculated replacement date,
3. Compare the actual component damage found during inspection, to the projected conditions, and then
4. Replace the component if necessary, or re-calculate a new optimised replacement date.

6. Discussion

In the RBLM optimisation model presented above, the following points warrant further discussion:

(1) Multi-component optimisation

It has been shown that the optimum year of replacement can be calculated when the net present value (NPV) of the maintenance action is maximised. If in a system of structures there is a budgetary constraint that does not allow for a series of actions to be undertaken in a given strategic planning period, further optimisation can be undertaken using the approach.
(2) Quantitative inputs

The technique requires a quantitative assessment of degradation/damage. This is at times expensive, time consuming and requiring simplifying assumptions to be made.

<table>
<thead>
<tr>
<th>Description</th>
<th>Action Year</th>
<th>Capital Cost</th>
<th>NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Str 1</td>
<td>2016</td>
<td>-14406972</td>
<td>-879853</td>
</tr>
<tr>
<td>Str 2</td>
<td>2016</td>
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<td>-3734112</td>
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<tr>
<td>Str 3</td>
<td>2012</td>
<td>-11852652</td>
<td>-2504706</td>
</tr>
</tbody>
</table>

Total NPV -7118677

**Figure 5:** Optimised action schedule leading to budget deficit arising due to two structures being replaced in the same year (2016)
<table>
<thead>
<tr>
<th>Description</th>
<th>Action Year</th>
<th>Capital Cost</th>
<th>NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Str 1</td>
<td>2017</td>
<td>-14406972</td>
<td>-884546</td>
</tr>
<tr>
<td>Str 2</td>
<td>2013</td>
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<tr>
<td>Str 3</td>
<td>2013</td>
<td>-11852652</td>
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</tr>
<tr>
<td>Total NPV</td>
<td></td>
<td></td>
<td>-7148132</td>
</tr>
</tbody>
</table>

**Capital Cost Action Schedule Summary**

<table>
<thead>
<tr>
<th>Year</th>
<th>Str1</th>
<th>Str2</th>
<th>Str3</th>
<th>Annual Total Cost</th>
<th>Annual Budget Limit</th>
<th>Deficit</th>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>26038606</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 6: Re-scheduling the year of action such that the costs lie within allocated budget
(3) RBLM models in complex systems

For more complex systems with increasing number of components and constraints, non-linear optimisation tools (e.g. those based on genetic algorithms) that are more powerful than the linear Solver in Microsoft Excel may be required;

(4) Direction of future relevant work

There is scope for further work on deriving failure estimates using expert elicitation and combining failure probabilities using Bayesian methods to update prior probability distributions with other data sources, e.g. combining specific failure databases with expert knowledge. More research is needed in assessing the use of genetic algorithms for optimisation in complex systems. Finally, further work is needed to incorporate a wider range of in-service equipment damage mechanisms to optimise RBLM actions.

7. Conclusions

The paper presents a quantitative risk analysis model to undertake run-repair-replace decisions in asset integrity management. The model implements an approach that ultimately minimises the risks associated with failures by optimally targeting resources at those components (within the asset system) identified as high risk.

8. Acknowledgements

The author wishes to acknowledge the financial support of TWI Ltd and the CICE (Centre of Innovative and Collaborative Engineering) at Loughborough University for this research.
This paper builds on a conference paper presentation by the lead author (Bharadwaj et al, 2007) and has gained from feedback received. The author is grateful to Chris Ablitt (TWI Ltd) and Julian B Speck (previously with TWI Ltd) for their perspectives on risk based practices in industry.

References


API Publication 2002, Risk-based Inspection, API Recommended Practice 580, American Petroleum Institute, USA.


E1: Event Tree Analysis (ETA)

Event Tree Analysis (ETA) is most suitable when the successful operation of a component depends on discrete (chronological) set of events. The initiating event is followed by other events, leading to a set of outcomes (consequences). Figure E-1 gives an example of an ETA.

The initiating event is the starting of fire. Possible events that follow this initial event are graphically depicted as shown in the figure. The analysis becomes quantitative when probabilities are assigned to each of these events. The probability of final outcomes can then be assessed by the rules of probability.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Starts</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Limited Damage</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Extensive Damage, People escape</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Limited Damage</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Not People</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Possible Fatalities</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Extensive Damage</td>
</tr>
</tbody>
</table>

Figure E-1: Event Tree Analyses (IET Health & Safety Briefing).
ETA is an effective tool for major accident risk analysis. The focus in an ETA is on the consequences of an initial event (failure) occurring and the likelihood of these consequences (in a quantitative model). However, the analysis can grow complex as the tree grows exponentially as more scenarios are considered. Hence ETA is generally used for a system with smaller number of components.

**E.2: FAULT TREE ANALYSIS (FTA)**

In a Fault Tree Analysis (FTA), the most serious outcome is selected as the top event. The fault tree is then constructed by relating the sequence of events which, individually or in combination could lead to the top event. A fault free is shown in figure E-2. A qualitative fault tree in itself provides a better understanding of various features of a system. Given failure (event) rates, the tree becomes quantitative.

FTA is mainly aimed at deriving the occurrence probability of the top (failure) event, given the probabilities for various events leading to it. Boolean algebra is used to connect the probabilities of events to get the probability of the top event. These probabilities are used in calculations using standard reliability principles that involve identifying cut sets (list of failure events such that if they occur so does the top event) and minimal cut sets (list of minimal, necessary and sufficient conditions for the occurrence of the top event).

FTA, like ETA, is an effective tool to analyse a system for an initial risk assessment. As described above, FTA is mainly used to ascertain the probability of failure of the top event.
However, this requires proper failure data that may at times not be available thereby restricting the use of FTA.

**E.3: FAILURE MODES, EFFECTS (AND CRITICALITY) ANALYSIS (FMEA)**

A FMEA answers the following basic questions:

- How can each component fail?
- What might cause these modes of failure?
- How often can the component fail in a particular mode?
Risk Based Life Management of Offshore Structures and Equipment

- What could be the effects if the failures occur?
- How critical are these failure modes?
- How is each mode detected?

A FMEA is often taken to a more advanced level – components within a system are ranked in terms of their criticality. This ranking may be qualitative or quantitative. The analysis then is called a FMECA.

Failure Mode and Effects Analysis (FMEA) or Failure Modes, Effects and Criticality Analysis (FMECA) are methodologies designed to identify potential failure modes for a product or process, to identify factors affecting the risk associated with those failure modes, to rank the issues in terms of importance and to identify corrective actions to mitigate the concerns. The FMEA required the identification of the following basic information:

- Components.
- Function of each component.
- Possible damage mechanisms and locations.
- Causes of damage mechanisms.
- Consequences of a failure.
- Current control.
- Possible mitigating actions.

A scheme for an FMEA is shown in figure D-3.
### FMEA

Component Name:
Function:
Failure rate:

<table>
<thead>
<tr>
<th>Failure Mode No.</th>
<th>Failure Mode Rate</th>
<th>Failure mode</th>
<th>Potential Causes</th>
<th>Effects on system</th>
<th>Detecting method</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fatigue</td>
<td>Incorrect Material</td>
<td>Routine Inspection</td>
<td>Critical</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collapse</td>
<td>Poor Weld</td>
<td>Maintenance</td>
<td>Negligible</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crack</td>
<td>Corrosion</td>
<td></td>
<td>Marginal</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Performance</td>
<td>Assembly error</td>
<td></td>
<td>Catastrophic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deterioration</td>
<td>Error in dimension</td>
<td></td>
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<td>Deformation</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Misalignment</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Leaking</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Falls off</td>
<td></td>
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<td></td>
<td>Vibrating</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Burnt</td>
<td></td>
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</tr>
</tbody>
</table>

*Figure E-3: FMEA format.*

Failure Mode and Effects Analysis (FMEA) or Failure Modes, Effects and Criticality Analysis (FMECA) are methodologies designed to identify potential failure modes for a product or process, to identify factors affecting the risk associated with those failure modes, to
rank the issues in terms of importance and to identify corrective actions to mitigate the concerns. The FMEA required the identification of the following basic information:

- Components.
- Function of each component.
- Possible damage mechanisms and locations.
- Causes of damage mechanisms.
- Consequences of a failure.
- Current control.
- Possible mitigating actions.

By identifying this information it is then possible to understand what components need to be considered in a management plan and how they are operated (e.g. environments, loading conditions). From knowledge of the service conditions it is then possible to identify how the life of the components may be consumed (What damage mechanisms may act on the component within the possible identified service conditions). Once we know how a component could fail it is then possible to look at what may be the consequences if it did actually fail. By understanding what fails, how it fails, what conditions affect the damage mechanisms, and what the consequences might be, it is possible to identify ways that these factors can be managed.

By having this thorough knowledge it is then possible to construct more generic techniques for assessing the risk of failure by qualitative or quantitative methods.
APPENDIX F: QUALITATIVE ANALYSIS: THE RISK MATRIX APPROACH

The risk matrix Approach

This is a common technique for risk analysis in which system components are broadly ranked (in qualitative terms) depending on their likelihood of failure and the consequence of failure. An example risk matrix is shown in figure F-1.

Figure F-1: Example of a risk matrix.
On the horizontal axis Consequences are qualitatively ranked as VL, L, M, H and VH representing Very Low, Low, Medium, High and Very High respectively. The vertical axis has the failure probability or the likelihood of failure in identical ranking terms. Risk increases as one moves away from the bottom left corner of the matrix. The risk could be because of a relatively high likelihood of failure or a high consequence value or, indeed, both. It must be noted that the ranking is relative to each other.

For example,

A possible qualitative ranking scheme for estimating the failure probability for components is shown below:

**Table F-1: Ranking based on the likelihood of failure**

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description (expected frequency of failure of the component during its lifetime)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Very high</strong></td>
<td>Failures continuously experienced ($\geq 10^{-1}$)</td>
</tr>
<tr>
<td>(Frequent)</td>
<td></td>
</tr>
<tr>
<td><strong>High</strong></td>
<td>Failures occur frequently ($10^{-2}$ and $10^{-1}$)</td>
</tr>
<tr>
<td>(Probable)</td>
<td></td>
</tr>
<tr>
<td><strong>Medium</strong></td>
<td>Failures occur several times ($10^{-3}$ and $10^{-2}$)</td>
</tr>
<tr>
<td>(Occasional)</td>
<td></td>
</tr>
<tr>
<td><strong>Low</strong></td>
<td>Unlikely but possible to occur during lifespan ($10^{-3}$ and $10^{-6}$)</td>
</tr>
<tr>
<td>(Remote)</td>
<td></td>
</tr>
<tr>
<td><strong>Very Low</strong></td>
<td>Very unlikely; occurrence may not be experienced at all ($\leq 10^{-6}$)</td>
</tr>
<tr>
<td>(Improbable)</td>
<td></td>
</tr>
</tbody>
</table>
A possible qualitative ranking scheme for estimating the severity of the consequence of failure of a component within a ship is shown below:

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description (expected cost of the consequence of failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>Failure has a knock down effect on the entire operation thus causing massive operational loss apart from rectification costs e.g. event involving loss of lives, Ship, Cargo, and spillage of Cargo causing widespread environmental damage. This would involve certain intangibles such as reputational loss etc.</td>
</tr>
<tr>
<td>High</td>
<td>Failure results in a stand-alone loss of operation apart from rectification costs. E.g. Ship becomes unavailable for sometime and Cargo is damaged</td>
</tr>
<tr>
<td>Medium</td>
<td>Failure results in Cargo damage and/or pollution</td>
</tr>
<tr>
<td>Low</td>
<td>Failure results in partial operational loss; damage may be rectified soon- no substantial loss of operation</td>
</tr>
<tr>
<td>Very low</td>
<td>Failure results in a very temporary production loss; damage is rectified</td>
</tr>
</tbody>
</table>

The analysis can become semi-quantitative if the Likelihood of Failure or Consequences are quantified to some extent. An example of how this could be achieved is shown below.

A variant of the above technique can be a ‘risk histogram’ that assigns relative likelihood and consequence values and normalizes them. The product of these values is then used to get a risk number (RN) which is the product of normalized likelihood value and normalized consequence value. RN values are used to construct the risk histogram (figure F-2). The values for likelihood and consequence can also be then used to construct a risk matrix.
(figure F-3). It may be noted that the approach here is semi-quantitative and the risk values used here are relative and not absolute. Also, there may be circumstances where a simple product between relative likelihood and consequence is not appropriate, particularly when consequences are high. For example, instead of

\[ R = P \times C \]

where \( P \) = the probability of failure and
\( C \) = the consequence of failure,

a measure of risk could be

\[ R = P \times C^n \]

where \( n \) is a number that enables risk to be evaluated on a non-linear scale.

Risk matrix and similar techniques are very useful tools to conduct a very preliminary risk assessment. Expert opinion, and not complex calculations or elaborate historical failure data, is often the only input that they require. This simplicity is, however, often its weakest point - the technique does not take the analysis further to determine how failures occur and what factors could mitigate risk.
Figure F-2: Example of using a measure of risk (RN) to highlight critical components.

Risk Matrix using normalized likelihood and consequence of failure values.

Figure F-3: Risk matrix using Risk Numbers (RN).
APPENDIX G: WIND TURBINES

G.1 A HISTORICAL PERSPECTIVE

Wind turbines (WT) are rotating machines that convert kinetic energy of the wind into mechanical energy and then electrical energy. WTs are variously called as wind generator, wind power unit (WPU) or wind energy converter (WEC). In the current context, the term wind turbine (WT) is used and is meant to include the structure on which turbines are mounted. If the mechanical energy is directly used by machinery for functions such as pumping or grinding, the machine is called a windmill.

Windmills have been used for at least 3000 years for grinding grain or pumping water (Burton, 2001). From the thirteenth century, horizontal axis windmills were used as an integral part of the rural economy. The use of windmills abated with the advent of cheap fossil-fuelled engines and the spread of rural electrification. The use of wind to generate electricity can be traced to the late nineteenth century with the 12KW DC windmill generator (WT) constructed by Brush in the USA. For much of the twentieth century, there was not much interest in using wind turbines on a large scale for power generation with the notable exception of the 1250 KW Smith-Putnam wind turbine constructed in the USA in 1941. This remained the largest wind turbine for about 40 years (Putnam, 1948).

In the early 1970s, the sudden increase in the price of oil spurred renewed interest in wind energy. Government funding for research, development and demonstration in this area became easier. The US, the UK, Denmark, Germany and Sweden were particularly more active in pursuing programmes at developing wind turbines. The price of oil has in recent
years again increased and there is a strong belief that alternative forms of energy need to be
developed to reduce the dependence on oil.

Other factors at play are:

- Increased awareness regarding the finiteness of earth’s fossil fuel reserves
- Increased awareness of the environmental impact of using fossil fuels
- Realization about wind as an abundant source of energy
- Technological capacity
- The vision and the political will to use wind in energy generation

G.2 MODERN DESIGN AND CONSTRUCTION

The principle of operation

A wind turbine is a machine that converts the power in the wind into electricity. As generators
of electricity, wind turbines need to be connected to some electrical network to be
‘transported’ from the point of generation to the point of consumption. Wind turbines these
days usually range from 0.5 MW to 5 MW capacity.

The energy conversion process uses the basic aerodynamic force of lift to produce a net
positive torque on a rotating shaft, resulting in the production of mechanical power at first and
then in its transformation to electricity in a generator. Wind turbines can generate power in
response to wind that is immediately available and it is not possible to store wind the way
conventional fuels can be stored. The output of a wind turbine is hence inherently fluctuating. The most one can do is to limit the output of a wind turbine to a level below what is possible for the wind to generate. Thus any system to which the wind turbine is connected must be capable of taking this variability into account.

Wind turbine systems when connected to larger systems serve to reduce electrical load to conventional generators enabling lesser consumption of conventional fuels. In smaller systems, there may be some energy storage with backup generators.

**Modern wind turbine design**

The most common wind turbines these days are the Horizontal Axis Wind Turbine (HAWT) in which the axis of rotation is parallel to the ground. A further classification is according to the rotor orientation - upwind or downwind of the tower, hub design (rigid or teetering), rotor control mechanism (pitch Vs stall, number of blades (usually two or three blades), and how they are aligned with the (free yaw or active yaw).

**Main sub-systems within a Horizontal Axis Wind Turbine (HAWT)**

The main components of the HAWT are shown in the figure F-1.

The principal subsystems of a typical horizontal axis wind turbine shown in the figure are:

- The rotor that in the current context includes the blades and the supporting hub;
The drive train, which includes the rotating parts of the wind turbine (excluding the rotor). It usually comprises shafts, gearbox, coupling, a mechanical brake, and the generator;

- The nacelle and mainframe, including wind turbine housing, bed plate, and the yaw system;
- The tower and the foundation;
- The machine controls;
- The balance of the electrical system, including power cables, switchgear protection, transformers and power converters.

The following variations in wind turbine design can be found:

- Number of blades (usually two or three);
- Rotor orientation, downwind or upwind of tower;
- Blade material, construction method, and profile;
- Hub design- rigid, tethering or hinged;
- Power control- aerodynamic control (stall control) or variable pitch blades (pitch control);
- Fixed or variable rotor speed;
- Orientation by self aligning action (free yaw), or direct control (active yaw);
- Synchronous or induction generator;
- Gearbox or direct drive generator.
Figure G-1: Schematic of a typical horizontal wind turbine

Appendix G: Wind Turbines
G.3 KEY COMPONENTS

Key Wind Turbine Components include:

(a) Rotor

The rotor consists of the blades and the hub of the wind turbine. These constitute the most important components within the wind turbine from the point of view of performance as well as cost. Most wind turbines these days have an upwind rotor with three blades although some down wind rotors and two blade rotors has been in existence. Single blade turbines have also been built in the past. Most intermediate sized wind turbines, especially those from Denmark, have fixed blade pitch and stall control. However, now the emerging trend is towards pitch control for larger machines. The blades are made of composite material- primarily fibre glass reinforced plastics, but sometimes wood/ epoxy laminates are also used.

(b) Drive Train

The drive train consists of all the rotating parts of a wind turbine with the exception of the rotor blades. There is a low speed shaft on the rotor side, a gear box, and a high speed shaft on the generator side. Other drive train components include the support bearings, one or more couplings, a brake, and the rotating parts of the generator. The gearbox increases the rate of rotation of the rotor from a low value, of the order of tens of rpm (rotations per minute), to the order of hundreds or thousands of rpm as required by the generator to generate electrical power. Some wind turbines, however, have specially designed generators that can operate at low speeds thereby obviating the need of a gear box. In WTs in which power is generated at a
Appendix G: Wind Turbines

higher machine rpm (i.e. turbines with gears) there is a low speed shaft leading up to the gear box, and a high speed shaft between the gear box and the generator.

(c) Generator

The generators take in mechanical power as input to give electrical power as the output. There are mostly two types of generators in use- induction generators and synchronous generators. Most of the turbines that are connected to the grid use induction generators. The main advantage of induction generators are that they are rugged, inexpensive, and easy to connect to the electrical network. However, an induction generator operates in a narrow band of speeds at slightly higher than the synchronous speed of the machine.

The synchronous generator offers some advantages over the induction generator- it is a variable speed machine which can operate in a wider range of wind speeds thus increasing energy capture. There is a general reduction in the wear and tear of the WT system by using synchronous generators. However, the generator itself is more complex than the induction machine requiring more of maintenance attention.

(d) Nacelle and Yaw System

This system includes the wind turbine housing, the machine bedplate or main frame, and the yaw orientation system. The mainframe provides for the mounting and the proper alignment of the drive train components and the nacelle cover protects the contents from the weather. The yaw mechanism aligns the rotor shaft such maximum energy from the wind can be harvested. The main component here is a large bearing that connects the main frame to the tower. Upwind wind turbines mainly use an active yaw drive, comprising a number of yaw
motors, each of which drives a pinion gear against a bull gear attached to the yaw bearing. This mechanism is controlled by an automatic yaw control system to which is connected a sensor to detect the wind direction. The system may also have a brake to hold the nacelle in the aligned position. Free yaw mechanisms, on the other hand, are commonly used on downwind wind turbines to self-align rotor with the wind.

(e) Tower and Foundation

This system includes the tower structure and the supporting foundation. There are mainly two types of towers (1) free standing types using steel tubes, lattice towers, and concrete towers and (2) guyed towers that are used for smaller turbines. The height of the tower is usually 1 to 1.5 times the rotor diameter, but in any case is normally 20 m (Manwell, J.F.; McGowan, J.G.; Rogers, A.L.; 2005)

Tower selection is influenced by the characteristics of the site. The stiffness of the tower is a major factor in wind turbine system dynamics because of the possibility of coupled vibrations between the rotor and the tower.

(f) The control system

The control system in general includes the following:

- Sensors e.g. Anemometer, Wind Vane, Rotor speed Sensor, Electrical power sensor, Pitch position sensor, vibration sensors, temperature and oil level indicators, etc.
• The Controller that is a system of hardware and software processing input signals from the sensors and generating output signals for the actuators

• Actuators included hydraulic or electric pitch actuator, generator contactors, switches for activating shaft brakes, yaw motors, etc.

The functions of a WT controller can be broadly classified into:

• Supervisory control that brings the turbine from one operational state to another for e.g., stand-by, start-up, stalling, shutdown, stop with a fault.

• Closed loop control which is usually a software based feedback mechanism that adjusts the operational state of the turbine such that it remains within pre-defined operating parameters

• The safety system that brings the system to a safe condition (usually in a state of rest) to pre-empt failure for e.g., the safety system might be tripped due to rotor over speed, excessive vibration, and other events such as a lightening strike.

(g) Clutches and Brakes

Clutches transmit torque when applied and do not do so when they are released. Clutches are typically applied by spring pressure and released through an active mechanical or electromechanical mechanism. Brakes function to bring a drive train or the yaw mechanism, for example, to a halt. The main difference between a clutch and a brake is that heating is a more important factor in a brake than a clutch.
G.4 RECENT DEVELOPMENTS IN THE WIND TURBINE SECTOR:

Current drivers for interest in wind farms are mainly the high cost of fossil fuels and the carbon emissions associated with the use of fossil fuels.

The UK Government’s Third Annual Report released in July 2006 on the implementation of the Energy White Paper (2003) underlines its policy to cut UK’s carbon emissions by 60% by the year 2050, with real progress by the year 2020 (DTI, 2002).

A shift from fossil based energy generation, which is responsible for a substantial proportion of CO2 emission, to the relatively clean energy generated from renewable sources is one of measures envisaged towards reducing carbon emissions. Wind energy is widely believed to be an abundant indigenous source of energy in the UK, and it is estimated that much of this renewable energy shall come from wind farms. Low CO2 emissions over the entire life cycle of wind turbine (and structure) manufacture, installation, operation and de-commissioning, have the potential to help limit climate change.

There continues to be progress in a number of areas in wind turbine technology: the rating of WT generators (in terms of the power output) has increased; there is better condition monitoring and better protection devices installed; two blade wind turbines are also being re-considered; factors such as noise pollution, aesthetics and yield have encouraged an increasing trend in locating Wind Farms offshore; floating Wind Turbines (obviating the need for foundations in the sea bed) are also being tested.