AUTHOR: SINHA, Y.

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PhD Theses

Optimisation of Offshore Wind Farm Maintenance

Yashwant Sinha

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This thesis is submitted towards the award of Doctor of Philosophy in Engineering.

"Determine that the thing can and shall be done, and then we shall find the way."

– ***Abraham Lincoln***

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ABSTRACT

The installed capacity of European Offshore Wind Turbines (OWT) is likely to rise from the 2014 value of 7GW to 150GW in 2030. However maintenance of OWT is facing unprecedented challenges and cost 35% of lifetime costs. This will be equivalent to £14billion/year by 2030 if current OWT maintenance schemes are not changed. However the complexities around OWT operation require tools and systems to optimise OWT maintenance.

The design of optimal OWT maintenance requires failure analysis of over 10,000 components in OWT for which there is little published work relating to performance and failure. In this work, inspection reports of over 400 wind turbine gearboxes (source: Stork Technical Services) and SCADA data (source: Shetland Aerogenerators Ltd) were studied to identify issues with performance and failures in wind turbines. A modified framework of Failure Mode Effects and Criticality Analysis (i.e. FMECA$^+$) was designed to analyse failures according to the unique requirements of OWT maintenance planners. The FMECA$^+$ framework enables analysis and prediction of failures for varied root causes, and determines their consequences over short and long periods of time. A software tool has been developed around FMECA$^+$ framework that enables prediction of component level failures for varied root causes. The tool currently stores over 800 such instances.

The need to develop a FMECA$^+$ based Enterprise Resource Planning tool has been identified and preliminary results obtained from its development have been shown. Such a software package will routinely manage OWT data, predict failures in components, manage resources and plan an optimal maintenance. This will solve some big problems that OWT maintenance planners currently face. This will also support the use of SCADA and condition monitoring data in planning OWT maintenance, something which has been difficult to manage for a long time.

ACADEMIC CONTRIBUTIONS

2015

J1. **Journal Publication:** Sinha, Y. and Steel, J.A., 2015. A Prognostic Decision Model for Offshore Wind Turbines Maintenance. *Wind Engineering*, *39*(5), pp.569-578.

J2. **Journal Publication:** Sinha, Y. and Steel, J.A., 2015. Failure Prognostic Schemes and Database Design of a Software Tool for Efficient Management of Wind Turbine Maintenance. *Wind Engineering*, *39*(4), pp.453-478.

J3. **Journal Publication:** Sinha, Y. and Steel, J.A., 2015. A progressive study into offshore wind farm maintenance optimisation using risk based failure analysis. *Renewable and Sustainable Energy Reviews*, *42*, pp.735-742.

J4. **Journal Submission**: Sinha Y., Steel J. A., (n.d.). A software package to store and analyse reliability data of wind turbine components and manage its maintenance. *IET Renewable Power Generation.* (Under Review).

2014

J5. **Journal Publication:** Sinha, Y., Steel, J.A., Andrawus, J.A. and Gibson, K., 2014. Significance of Effective Lubrication in Mitigating System Failures—A Wind Turbine Gearbox Case Study. *Wind Engineering*, *38*(4), pp.441-449.

J6. **Poster Presentation:** Sinha Y., Steel J. A., Andrawus J. A., Coull F., 2014. Offshore Wind Turbine Maintenance and Sparesholding Optimisation. *ETP Conference, Dundee, 23-24 April 2014.*

2013

J7. **Journal Publication:** Sinha, Y., Steel, J.A., Andrawus, J.A. and Gibson, K., 2013. A SMART software package for maintenance optimisation of offshore wind turbines. *Wind Engineering*, *37*(6), pp.569-577.

J8. **Poster Presentation:** Sinha Y., Steel J. A., Andrawus J. A., Gibson K. 2013. Significance of Gearbox Lubrication in Wind Turbines. *ETP Conference, Edinburgh, 16-17 April 2013.*

J9. **Panel Member for Debate:** Renewables will ensure that Scotland keeps the lights on in 2020. *ETP Conference, Edinburgh, 16-17 April 2013.*

2012

J10. **Poster Presentation:** Sinha Y., Steel J. A., Andrawus J. A., Meredith M. 2013. Offshore Wind Turbine Maintenance Optimisation. *ETP Conference, Glasgow, 22-23 March 2012.* (**3rd Prize**)

Journal Papers in the process of submission

J11. **In Progress**: Sinha Y., Steel J. A., Andrawus J. A., A study of compensatory provisions and practices to improve availability of offshore wind turbine components. (Under internal review).

J12. **In Progress**: Sinha Y., Steel J. A., Andrawus J. A., Using Condition Monitoring data to translate failures in wind turbine components and optimise maintenance. (Under internal review).

PLEASE NOTE:

Parts of the chapters in this thesis have either been published in above journals (J1, J2, J3, J4, J5, J7) or are part of journal papers in the process of submission (J11, J12).

i. Chapter 1 is part of journal papers J2 and J3

ii. Chapter 2 is part of journal paper J2, J3 and J7

iii. Chapter 3 is part of journal paper J2, J3, J4, J5 and J11

iv. Chapter 4 is part of journal paper J2

v. Chapter 5 is part of journal paper J2, J4 and J7

vi. Chapter 6 is part of journal paper J1 and J7

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List of Abbreviations

(S,O,D)	(Severity, Occurrence, Detection)
AES	Auxiliary Electrical System
AF	Anticipated Failure
ANN	Artificial Neural Network
CA	Criticality Analysis
CBM	Condition Based Maintenance
CBPM	Condition Based Predictive Maintenance
CM	Condition Monitoring
COCA	Cost and Operation Critical Assemblies
CPCP	Component Parallel and Compensation Parallel
CPCS	Component Parallel and Compensation Series
CSCP	Component Series and Compensation Parallel
CSCS	Component Series and Compensation Series
DMS	Database Management System
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
ERP-OWT	ERP software for OWT
FBM	Failure Based Maintenance
FLFA	Function Level Failure Analysis
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes Effects and Criticality Analysis
$FMECA^+$	FMECA plus (new framework of FMECA)
FT	Failure Type
HAZOP	Hazard & operability Analysis
HLFA	Hardware Level Failure Analysis
HSE	Health, Safety and Environment
ISO	International Organisation for Standardisation
LCoE	Levelised Cost of Electricity
MRP	Material Required Planning
OA	Optimising Algorithm
OF	Observed Failure
OFR	Overall Failure Result
OnWT	Onshore Wind Turbines
OWT	Offshore Wind Turbines
OWT-COCA	Cost and Operation Critical Assemblies for OWT

OWT-MOT	OWT Maintenance Optimisation Tool
PF	Predicted Failure
QA	Qualitative Analysis
RBD	Reliability Block Diagram
RC	Root Cause
RCM	Reliability Centred Maintenance
RD	Relational Database
RPN	Risk Priority Number
SCADA	Supervisory Control and Data Acquisition system
TBM	Time Based Maintenance
t-FMECA	Traditional FMECA
UK	United Kingdom
WT	Wind Turbine

VARIABLES

Symbol	Comments
A	Availability
A_O	Original Availability
A_C	Changed Availability
C_p	Cost of generating power
MWh	Megawatts of power generated in one hour
P	Productivity
P_O	Original Productivity
P_C	Changed Productivity
R	Reliability
R_O	Original Reliability
R_C	Changed Reliability
e	Change in value of Availability
P^*_+	Positive change in productivity due to maintenance
T_a	Time OWT is available for power generation (hr)
T_d	Time OWT is not available due to failure (hr)
T_r	Time OWT is down due to repair (hr)
T_R	Turbine Rating
P_P	Profit Percentage (=25%)
P_I	Insurance Premium
N	Number of Wind Turbines in a Wind Farm
k	Time period when generating partial power
x	Percentage of actual power generated
λ	Fraction of total time in a year when favourable wind is available
T_{AC}	Time Period for Accident
P^*	Change in productivity due to maintenance
P^*_-	Negative change in productivity due to maintenance

CHAPTER 1. INTRODUCTION

1.1. Background

Wind is defined as a "*current of air moving approximately horizontally, especially one strong enough to be felt*" (Cambridge, 2016). Its speed and direction are influenced by rotation of earth (Coriolis Forces), temperature and pressure gradients, landscape, altitude and frictional heat generated by the motion of air over landscape (Watson, 2011). Such a perpetual nature of origin makes wind an infinite reserve of kinetic energy. This energy can be converted to electricity using Wind Turbines (WT) without generating polluting by-products during the electricity generation process like CO_2 emissions. As 'Kyoto Protocol' (Chazournes, 1998) requires countries to control their CO_2 emissions, the use of WT and other renewable energy based power generating systems is on the rise.

The United Kingdom (UK) contains vast areas of unused agricultural, pasture and hilly terrains where wind speeds (>2.5m/s) are sufficient to operate WT (Figure 1.1). It also has over 114,000 km^2 of coastline with the North Sea, North Atlantic Ocean, Celtic Sea and the English Channel where unobstructed high speed wind can be used to generate electricity. As a result many Onshore Wind Turbines (OnWT) and Offshore Wind Turbines (OWT) have been installed in onshore and offshore locations across UK. By 2013, the installed capacity of OWT and OnWT in the UK were 3.6GW and 6.4GW respectively. However, whereas the growth in the installed capacity of OWT in 2012 was 46% over the previous year (Martinot and Sawin, 2012), the installed capacity of OnWT grew by only 17%. The higher growth rate of OWT can be attributed to factors that generate more power from OWT that reduces the payback period on OWT investment. These factors include unrestricted space and higher speed but low turbulent winds in the offshore sites (Boccard, 2008).

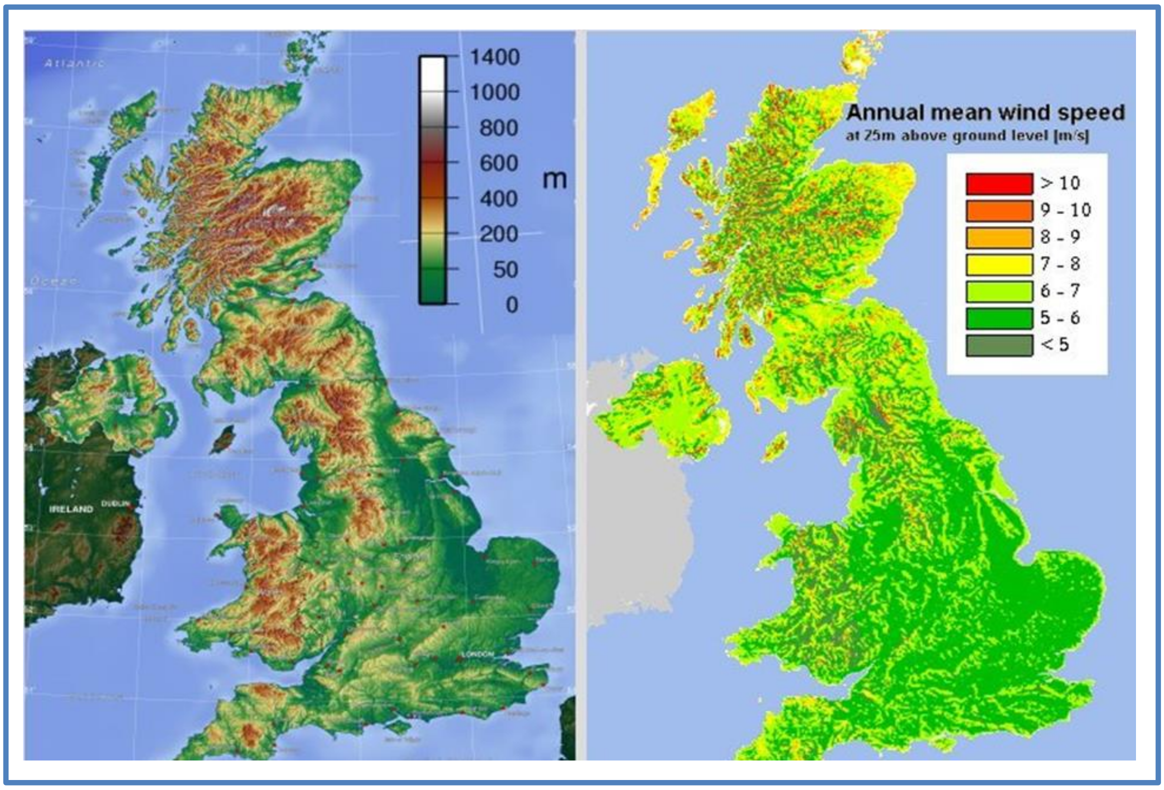


Figure 1.1 Shows the topography and annual mean wind speed distribution in UKI

1.2. Offshore Wind Turbines

The first offshore wind farm was installed in Denmark in 1991. Ever since then the installed capacity of OWT has seen momentous growth. The evolution of OWT technology has made it possible to install OWT at distances greater than 20km in offshore sites (Sawyer and Rave, 2010). In Europe, the installed capacity of OWT generated 4GW (Nayak, 2011) in 2011 that doubled in 2014 (7.34 GW) (European Wind Energy Association, 2014). Such high growth in OWT installed capacities have been reported by many other countries (Chen, 2006). In fact the worldwide installed capacity of OWT grew at 250%/year in last decade. Moreover UK is a pioneer and leader in OWT and its technology. In 2015, the installed capacity of OWT in the UK was amongst the highest in the world at 4GW (Renewable UK, 2015). However being at the forefront in using OWT technology,

[I] Estimating mean wind speeds and their profile. (2016). [online] Wind-power-program.com. Available at: http://www.wind-power-program.com/windestimates.htm [Accessed 5 Mar. 2016].

UK is also facing unique challenges of operating WT in offshore sites like the unexpected higher Levelised Cost of Electricity (LCoE), intermittency in electricity generation, high cost of transportation and issues with storage of excess energy (Martinot and Sawin, 2012). Although improvements made in the reliability of components reduced the LCoE of OWT (Burrett et. al., 2009) however the LCoE of OWT is still amongst the highest in the energy sector (Figure 1.2).

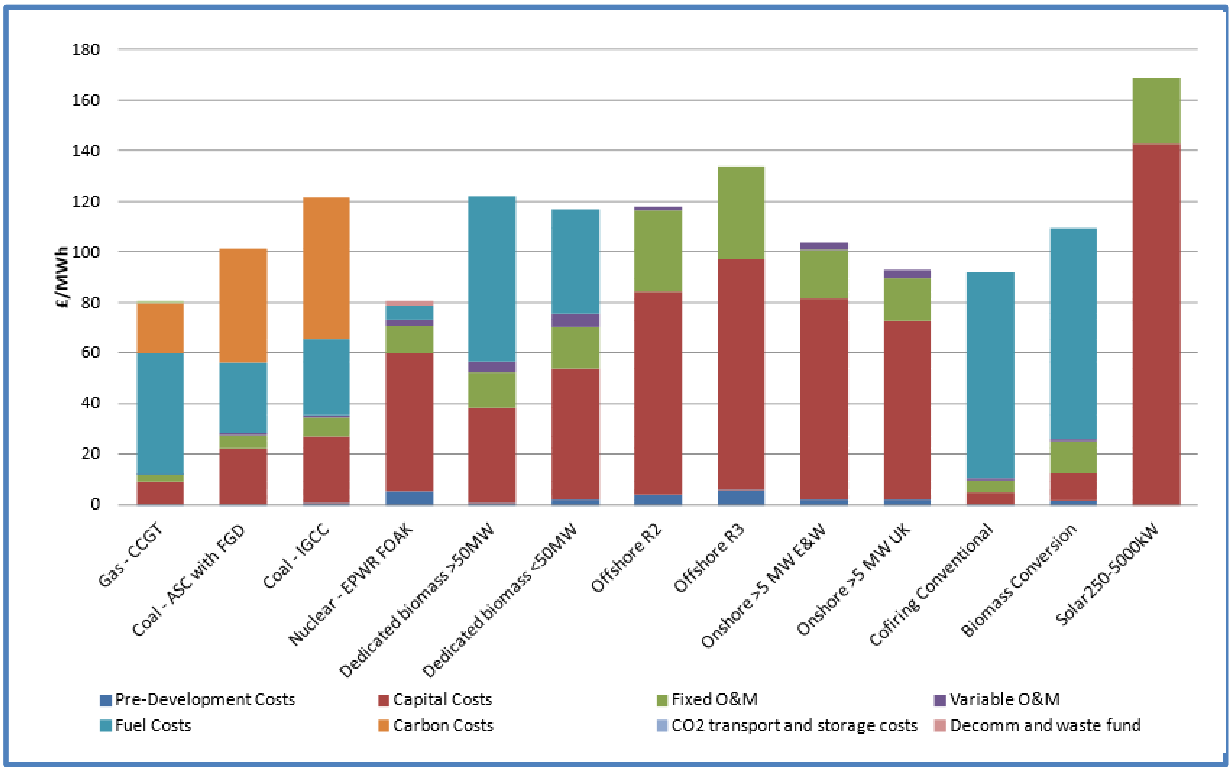


Figure 1.2 Levelised cost of projects starting in 2012

(Source: Department of Energy & Climate Change, 2012)

A comparison of the LCoE of different power generation systems is shown in Figure 1.2 (Department of Energy & Climate Change, 2012). It is evident from Figure 1.2 that the LCoE of OWT is amongst the highest amongst power systems. However unlike the LCOE of other power systems, the LCoE of OWT is seen to depend only on the installation and maintenance costs. As the cost of OWT installation will go down with increase in the number of installations, it is needed that work is done to economise the maintenance cost to lower the LCoE of OWT.

It is observed from Figure 1.2 that the contribution of maintenance cost in the LCoE of OWT and OnWT are about 30% and 20% respectively. As the LCoE of UK's OWT R2 and OWT R3 projects are seen to be £118/MWh and £134/MWh respectively from Figure 1.2, the cost of maintenance for OWT R2 and OWT R3 projects evaluate to £35/MWh and £41/MWh respectively. This is twice the cost of maintaining OnWT (£19/MWh). However in spite of the higher costs of OWT installation and maintenance, offshore location offer conditions that generate more power from WT (Koch and Retzmann, 2010) and so offers added financial benefit to operators. This work identifies challenges linked to OWT maintenance and proposes potential solution to economise OWT maintenance. This will bring added financial benefits to the operators and customers of OWT.

1.3. Current challenges with OWT maintenance

The OWT operate in stochastic offshore environments where accessibility is limited, operating costs are higher than onshore locations and prediction of failures/faults in OWT components is difficult to generalise. As a result OWT maintenance is largely based on personal judgements/experience. This results in either a Failure Based Maintenance (FBM) and/or Time Based Maintenance (TBM) schemes. However experiences from several industries have shown that FBM and TBM are costlier to plan and implement than Condition Based Maintenance (CBM) (Ait-Kadi et. al., 2009). However operators often use FBM and/or TBM schemes to maintain high availability of OWT in spite of the randomness that is introduced in planning maintenance and the recurring use of expensive resources. All these avenues raise the operating cost of OWT and so raise the LCoE of OWT.

Many industries have used CBM to economise maintenance. In CBM, maintenance of machines components is planned only when an analysis of the condition monitoring data shows failures and faults in machine components.

However an OWT contains more than 10,000 components for which there are limited tools and expertise to manage condition monitoring data and plan CBM. This result in OWT operators making use of alternate maintenance schemes like TBM and FBM which incur higher costs. In addition, a reliability database for OWT components is yet to be compiled that will store information about failures and faults in OWT components. Such information is needed to predict failures and plan an economical CBM based maintenance scheme.

However the stochastic nature of offshore agents like wind, humidity and waves, also result in premature failures in OWT components and add to lifetime maintenance cost (2nd International Electrochemical Commission, 2007). As OWT is a relatively new technology, the effect of such stochastic agents on OWT operation is not fully understood. The limited ability to predict failures result in over and/or under maintenance activities that influences inventory management related costs. The cost of offshore transportation is also very high and rises with payload and offshore distance. Any deviation made to an already planned maintenance, either due to absence of spares or transportation, results in high resource retention cost. It also results in higher carbon storage and its transportation costs (Karyotakis, 2011) and so unplanned maintenance incurs higher cost for OWT than planned maintenance.

A greater challenge for OWT is the diverse nature of operating conditions in which it operates. These conditions influence power output from OWT, failure pattern in its components and so has a financial impact. The diversity arising due to operating conditions is evident from studies that have tried to identify failures and faults in wind turbines (Ribrant and Bertling, 2007; Chen, Matthews and Tavner, 2014). So, any work on optimisation of OWT maintenance needs to be site specific. However any fundamental work towards maintenance optimisation also has common avenues whose study will avoid duplication of efforts for sites.

So in this work on designing optimal maintenance for OWT, a generic framework of OWT maintenance is designed that can be altered to suite site specifications. Such work involves tasks like designing and developing tools and systems that can store and analyse condition monitoring data, perform failure analysis and optimally manage resources. Such work is critical in planning and the success of OWT maintenance. The design of such supporting tools and its use in planning maintenance is vital for controlling OWT maintenance costs. This is because if OWT maintenance strategies are not supported, it will cost £6.2billion/year by 2020 to maintain OWT (calculated using LCoE = £135/MWh, maintenance cost = 35% of LCoE (Walford, 2006), Capacity = 75GW (Wiser and Bolinger, 2008), Availability = 50%, Efficiency = 40%). Hence design and development of tools and systems to support in OWT maintenance is very much essential.

1.4. Historical and Modern Maintenance Schemes

Historically maintenance was classed as Corrective Maintenance and Preventive Maintenance (Gits, 1992; Herbaty, 1990) however Predictive Maintenance, a type of Preventive maintenance, is becoming popular as it costs less and uses less resource than Corrective Maintenance (Eade, 1997; Marquez, 2012). The modern and traditional maintenance schemes are given in Figure 1.3.

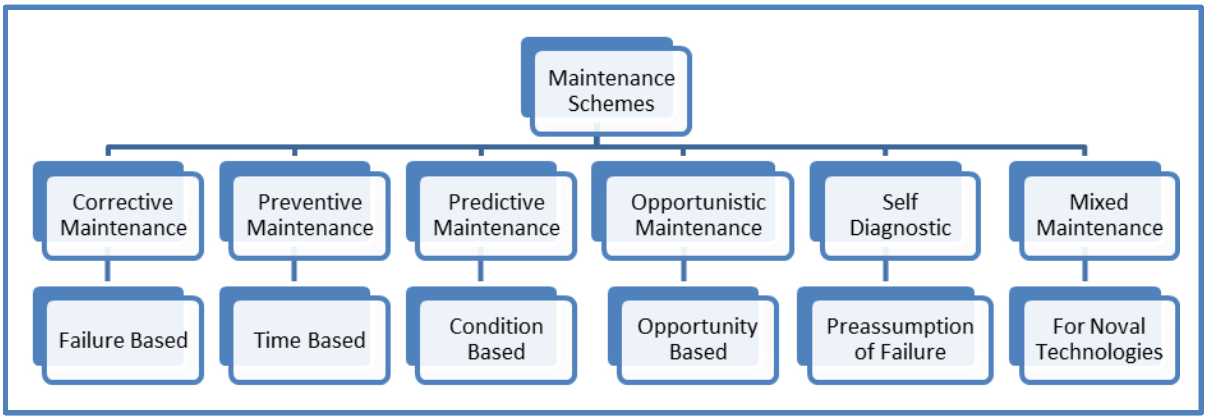


Figure 1.3 Shows various modern and traditional maintenance schemes

Over the years significant contributions have been made to the maintenance schemes that are shown in Figure 1.3. This has led to their unique identities and identified the scope of use. For example, although Predictive Maintenance and Opportunity Maintenance are both derivatives of Preventive Maintenance the strategy used to plan and implement them differ as, Opportunity Maintenance can be postponed till the time it is economically viable. Likewise, Predictive Maintenance is preferred for critical components of expensive machineries however Corrective Maintenance is preferred to reduce the operating cost of machineries nearing end of their lifetime. Similarly for innovative machines, for which failure data may not be available to predict failures, a mix of various maintenance schemes may be used during their lifetime. As OWT are innovative technologies and given that challenges are linked to offshore based maintenance, this study recommends building a Self-Diagnostic system to detect and rectify failures in OWT as much as reasonably possible. This will reduce financial losses from OWT downtime due to inaccessible of OWT. It will also reduce incidences of failures and faults introduced in OWT due to human negligence or incorrect maintenance (Dhillion, 2009). So in the long term, a Self-Diagnostic system will be a cost effective plan (Endrenyi, et. al., 2001).

A Condition Based Maintenance (CBM) is a type of Preventive Maintenance scheme where maintenance is planned based on the present condition and past failure patterns of a component. If such information is available for OWT components, it can be used to design CBM and so economise OWT lifetime costs (Paima, et. al., 2010; Zaher and McArthur, 2007; Li, He and Kong, 2010). This will also be useful in reducing costs linked to spares (Ribrant, 2006). However current CBM based OWT maintenance incur significant cost (May and McMillan, 2013; McMillan and Ault, 2007; Van de Pieterman et. al., 2011). A possible issue with such CBM based OWT maintenance can be due to non-adherence to ISO 17359 guidelines that are a prerequisite for planning CBM. According to ISO 17359 guidelines, a prerequisite for planning CBM based maintenance is to analyse the failures of components in a machine and identify their criticality. However such information is retained by operators due to their commercial value and is not readily available for OWT (Ding, et. al., 2007). This limits the ability to plan CBM and make use of supportive systems like Artificial Neural Network (Tian and Jin, 2011) to optimise the planning and execution of OWT maintenance.

However as a starting point, a possible solution to the above issue is to identify generic components in OWT, determine their failures, identify their root causes and establish their criticality. Such a mapping between failures and their root causes, and identification of their criticality, will support predict the nature of component level failures when their root causes are known to occur. In view of >10,000 components in OWT, ranking of failures according to their criticality will support optimise maintenance. However planning for such a technique requires tools which will otherwise be time consuming and very costly to implement. The use of such tool to optimise OWT maintenance has benefits over other tools that make use of statistical methods to give a numerical value of failure prediction. However a tool that performs failure analysis offers better understanding about the nature of failures and faults in OWT components and identifies the root causes of failures and faults. Such information is critical to plan spares, control occurrence of failure in future and so optimise performance and maintenance. This has financial benefits and so such a tool is very much needed for OWT.

1.5. Condition Monitoring

Condition Monitoring (CM) is a method wherein physical and chemical properties of machine components are studied to establish failures and faults. A knowledge of the methods used to perform CM and practices, that are used to analyse CM data, are prerequisites for planning a CBM for OWT. The CM methods use waves (like vibration, ultrasonic, acoustic, radio, shock), viscosity and/or composition of lubricating oil, electrical parameters, changes to process & performance parameters, temperature, strain energy and other parameters to establish failures and faults in components (Tandon, 1992; Yoshioka, 1995; Tan, 1990; Morando, 1988; Verbruggen, 2003; Schoen, et. al., 1995; Seo and Lee, 1999; Zaher and McArthur, 2007; Dolinski and Krawezuk, 2009; Papadopoulos, et. al., 2000; Fantidis, Potolias, Bandekas, 2011). In view of 10,000 components in OWT, the time and cost required to use CM will be very high. However advances have been made in CM techniques that support their implementation and so economised their use. This includes techniques that use electrical signals to detect failures using their signature frequencies (Al-Ahmar, et. al., 2008; Amirat, Choqueuse, Benbouzid, 2010) and use of signal processing methods like Artificial Neural Networks (Guo and Wu, 2010), Fast Fourier Transformation (El Hachemi, 2000), Time-Frequency Representation, Time Scale Decomposition (Cusido, et. al., 2008) and AM/FM technique (Stack, Harley and Habetler, 2004). These make it possible to detect failure at the component and assembly levels using CM signals (Yao, Shan and Su, 2006).

The Supervisory Control and Data Acquisition (SCADA) system are often used to collect CM data from the WT controller and transfer it to remote site for analysis purposes. In this way SCADA systems cut down costs linked with offshore travel and use of manpower for performing CM. Some modern SCADA systems have inbuilt capability, although limited, to detect failures from CM data (Igarashi and Hamada, 1982; Ribrant, 2006). Some SCADA systems used in WT are Wind Power Dashboard, CONCERTO and WindNet (Sainz and Liombart, 2009; Tan, Irving and Mba, 2007). The WT controller obtains CM data from sensors attached to monitored components in OWT. However not all sensors need to be exclusively installed for CM purposes as many sensors are already installed in WT to support WT operation (Yang, Li and Wang, 2008; Caselitz, et. al., 1997). For example sensors attached to WT nacelle and blades align them in the direction of incoming wind and reduce failures arising due to unwarranted stress developed in their components. The sensors attached to lubricating systems can be used to detect deadly smoke that arises from the combustion of leaking lubricating oil and so warn maintenance people against working in the nearby confined spaces. The sensors that provide support for WT operation can also be used to plan OWT maintenance (Johnson and Fleming, 2011; Wei and Liu, 2010; Lu, et. al., 2009) and so the overall expenditure for implementing CM can be lower than expected.

1.6. Optimisation of OWT maintenance

Several studies have taken diverse avenues to optimise WT maintenance. These include works on avenues identified by Rademakers et. al. (2003) like optimal use of transportation and number of personal engaged in maintenance by Van Bussel and Bierboom (2003) and Jacquemin (2007). Some other works used CBM and Risk Based Inspection (Sorensen, 2007), Monte Carlo Simulation (Durstewitz, et. al., 2004), Modelling System Failure and Delay Time Model (Andrawus, 2008) and Artificial Neural Network (Tian and Jin, 2011) to optimise WT maintenance. Some other works used Bayesian Network (Nielsen and Sorensen, 2010) and Fuzzy Logic (Bashiri, Badri and Hejazi, 2011) to design CBM for WT. However the results obtained by these studies and their inferences vary widely as the focused scope of these studies and the difficulty in obtaining WT operational data for validation, limit the practical use of these models. Also, the statistical techniques used by these studies do not offer the flexibility needed to build a generic CBM maintenance model as described in ISO 17359 guidelines like the essential research into identification of components and failure analysis. As a result this work uses Qualitative Analysis methods to perform scenarios based case studies in an attempt to optimise OWT maintenance.

1.7. Need of a tool for failure analysis

It was mentioned in Section 1.4 that there is a need to analyse failures and map them to their root causes in order to plan a CBM for OWT. However stochastic conditions result in several different root causes of failures that cause failure in OWT components. On average, an OWT shows 2.2 major and several small failures each year (Bussel, 1999; Nilsson and Bertling, 2007) but the limited ability to predict the nature of failures and their root causes result in non-optimal maintenances. Such non-optimal random maintenances cost 66% of the total maintenance cost incurred during the lifetime for OWT. A technique that can predict failures, identify their nature and root causes and, recognise the effected components, will invariably cut down maintenance costs. However such a technique is complex to build due to the extent of root causes and failure correlations that exists for OWT as seen below.

The component level failures in OWT can arise due to several causes. These include environmental conditions like high wind speed and turbulence, ice build-up, temperature and humidity (Tavner, 2010; Mouzakis, Morfiadakis and Dellaportas, 1999). The marine environment also results in corrosion and fatigue related structural failures (Erich, 2005). Failures can also be assembly specific like in gearboxes that arise from corrosion, failure of lubrication and cooling systems, debris build-up in lubricating oil and improper amount of lubricating oil (Lai, Ioannides and Wang, 2008; Pasaribu and Lugt, 2012). Failures also arise in structural components due to age and overworked components. Manufacturing defects, installation errors, misaligned parts, sensor failure (Ye, et. al., 2009)

(Becker, 2006), failure of insulation against temperature, humidity, contamination, dirt (Taylor, 2010; Tavner, 2012), bearing seizure (Bloch and Geitner, 2012), fracture, blockage, pitting and other corrosive failures also result in partial/complete failure in various OWT components. The Yaw system can fail due to differential loading (Caselitz and Giebhardt, 2005) while problems in diode, transistor, thyristor and IGBT also give rise to failures and faults (Dongxiang et. al., 2008; Amirat, Choqueuse and Benbouzid, 2010). In some instances excessive frictional energy, that result in unwanted expansion, cavitation and material defects are also known to cause failure of the main shaft (Elforjani and Mba, 2009). In addition design limitations, defects, application and maintenance issues also result in component level failures (Heywood, Lapworth, Hall and Richardson, 2005; Heathcote, 2011).

The extent of relationships between root causes and their failure requires a tool to perform such a mapping. Such a tool is required as for OWT such relationships can result in over 250,000 combinations of failures and their root causes (calculated using 10,000 components in OWT that fail in 5 way due to 5 different root causes). Such a tool will support identify root causes of failure, analyse failures for their short and long term impact, identify other components that may potentially be effected by the occurrence of a given root cause of failure and to predict the occurrence of a failure if its root cause was known to occur. Such information will enable plan a prognostic CBM that will reduce maintenance deferments and delays due to unavailability of resources (Karki and Billinton, 2004; Leite, Borges and Falcao, 2006). A prognostic maintenance also controls catastrophic failures in OWT by rectifying minor failures at an early date. Although industry experiences for OnWT and OWT differ, a tool that can map failures to their root causes and analyse failures, can be universally applied and so benefit operators who would like to use one good practice for all types of WT.

1.8. Research aim, objectives and its impact

This chapter identified the importance of building supportive tools for OWT maintenance. It was also identified that to achieve the benefits offered by CBM there was a need to perform component level failure analysis for OWT. As such this work aims to develop a tool to perform failure analysis of OWT components as per the unique requirements of OWT operators and, design and develop a maintenance planning and optimisation tool for OWT. However failure analysis requires knowledge of OWT components, the nature of their failures and root causes, and the conditions that give rise to such root causes. As a result this work aims to achieve the following objectives,

1. identify cost and operation critical assemblies in OWT
2. identify a technique using which failures and faults and their root causes can be determined for OWT components
3. identify/design a failure analysis method for use with OWT components
4. demonstrate the use of this failure analysis method for critical assemblies
5. Design and develop a tool to perform failure analysis using above method
6. Design and develop an OWT maintenance planning and optimisation tool

An implication of this work will be in controlling the direct expenditures on OWT maintenance that will invariably reduce the lifetime cost incurred on OWT and so will economise the LCoE of OWT. In order to achieve these objectives, this work makes use of the following methodology,

Step 1. Perform literature survey of WT assemblies and components, failure detection and analysis methods, optimisation methods, challenges with failure analysis techniques, stakeholder of OWT maintenance tool and design requirements for OWT maintenance tool

Step 2. The usefulness of condition monitoring data in establishing failures and faults, and their root causes, for OWT components will be analysed

Step 3. A suitable failure analysis method will be either identified from existing techniques or will be developed for analysing and ranking of failures in OWT components

Step 4. Based on above failure analysis method, a failure analysis tool will be designed and developed. It will be tested for its usefulness in the critical assemblies of OWT

Step 5. A failure analysis method based OWT maintenance planning and optimisation tool will be planned and developed.

A number of journal articles have been published (Page 5) that's shows the progress made in achieving the above aims and objectives.

In order to realise the objective stated in Step 2, data from the following sources were used (samples provided in Appendixes).

1. SCADA Data: Shetland Aerogenerators Ltd., Lerwick, Shetland, UK
    a. 3 V47 Vestas make WT (Installed 2000): 4 month SCADA data
    b. 2 V52 Vestas make WT (Installed 2003): 4 month SCADA data

The SCADA data provides average, maximum, minimum and standard deviation values of the monitored parameters over a 10 minute interval. As maximum and minimum values over a 10 minute interval are individual instances, the average values of monitored parameters were usually taken in the analysis. The standard deviation values were considered while calculating turbulence intensity of wind. Several fields of the SCADA data contained erroneous or no data, and so such instances were neglected during the analysis.

2. Inspection Report: Stork Technical Services, Aberdeen, UK
    a. Visual analysis reports of 400 gearboxes
    b. Lubricating oil analysis reports of 400 WT gearboxes
    c. Vibration analysis reports of 400 WT gearboxes

These inspection reports relate to WT operating in several European countries. Although many reports used a standard framework for reporting the results, many of them also used different languages and reporting styles. The operational age of several WT gearboxes were also not certain. As a result, according to the objective of analysis, only appropriate inspection reports were analysed. A sample of this report is given in Appendix B (I) and Appendix B (II) .

1.9. Layout of Theses

This theses is divided into 6 chapters. In Chapter 2, a literature survey into the background of this research has been given. It discusses about usefulness of failure analysis and methods using which it can be achieved. It also discusses about generic components in WT. In Chapter 3 the usefulness of condition monitoring has been illustrated with the help of case studies. The chapter shows how by making use of the results obtained from failure analysis, failures can be predicted. The design of a failure analysis based CBM scheme has been shown. The design and development of the failure analysis tool and, maintenance planning and optimisation tool has been discussed in Chapter 4. In Chapter 4, some results obtained from such a design endeavour has been shown. In Chapter 5, the usefulness of a maintenance decision model for OWT has been developed. The model shows conditions under which maintenance of OWT should be planned. Some mathematical equations have also been developed. In the last chapter, i.e. Chapter 6, a summary of this research work, a list of some future works and some remarks have been made.

1.10.Summary

This chapter identified the benefits of using OWT in electrical power generation. However it was recognised that added financial benefits would be obtained if the currently high cost of OWT maintenance is economised. This can be achieved by planning CBM based maintenance for OWT however it will require supporting tools that can perform the repeated and complex task of failure analysis in over 10,000 components in OWT and plan an optimal maintenance. Such a tool is central to designing a CBM for OWT and offers the facility of identifying root causes of failures, effected components and the nature of their failure / fault. This information is critical for OWT operators to plan resources, rectify failures and circumvent their future occurrence. Such a prognostic CBM for OWT will also improve the reliability of OWT, improve productivity and lower the frequency of failures and faults. This will invariable reduce maintenance cost and lifetime cost of OWT.

CHAPTER 2. Literature Review

2.1. Introduction

Offshore Wind Turbines (OWT) converts a greater proportion of wind energy into electricity than Onshore Wind Turbines (OnWT) (Koch and Retzmann, 2010). So in spite of the higher Levelised Cost of Electricity (LCoE), OWT has benefits over OnWT. The financial benefits from OWT can be enhanced if the operation and maintenance cost of OWT is economised. This chapter explores background information and challenges into optimisation of OWT maintenance. The chapter identifies critical assemblies in OWT, establishes failures in these assemblies, provides an overview of failure analysis methods and identifies the prerequisites for designing tools to optimise OWT maintenance. References are made to studies having different but similar approach to optimise OWT maintenance plan.

2.2. Offshore Wind Turbines Vs Onshore Wind Turbines

A Wind Turbine (WT) is built using many electrical, mechanical, electronic, communication, structural and computing assemblies and their components. It fundamentally contains an assemblage of blade, main shaft, gearbox, generator, transformer and a controller. These are positioned inside an enclosure called the nacelle. The nacelle is positioned above the ground using a tower. In onshore locations their heights are about 1.5 times the blade diameter while in offshore locations such heights are >80m above the sea level for detection by the radars of vessels and ships. The tower is fixed to the ground or the sea bed using concrete or steel foundation (Martinot and Sawin, 2012). The OWT are usually of higher rating than OnWT (>2MW) however functionally, the assemblies and components inside the nacelle of OWT and OnWT are similar. The OWT have deeper foundation, inbuilt cranes to move man and material and, docking and helipad for transportation (Junginger, Faaij and Turkenburg, 2004). They also have special lighting arrangements to enable maintenance works in humid and low visibility. The OWT are also linked using satellite for telemetry and tracking (Manwell, McGowan and Rogers, 2010; Wang and Wang 2010).

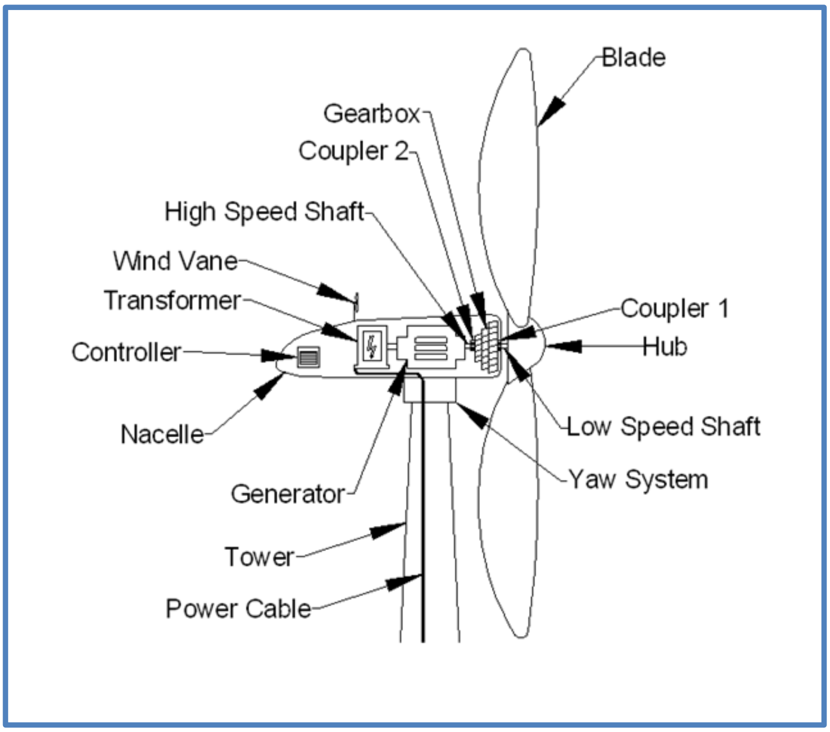


Figure 2.1 Shows a schematic sketch of key wind turbine assemblies

Although tower and foundation are important assemblies of OWT, they fail in exceptional cases like natural disaster. So this work is focused on optimising maintenance of assemblies inside the nacelle of OWT. A maintenance strategy developed using failure and its root cause analysis for assemblies inside the nacelle of OWT will be equally applicable for OnWT as such assemblies are functionally similar. As a result such a maintenance strategy can be applied to all types of WT. Such a strategy will also benefit OWT maintenance planners by incorporating the learning outcomes from OnWT maintenance into OWT. As a result this work aims to develop an optimal maintenance strategy for OWT based on the use of failure analysis.

2.3. Constituents of OWT Nacelle

The EU FP7 ReliaWind Consortium proposed a list of generic components in the nacelle of WT (Wilkinson, et. al., 2010) that are functionally similar for both OnWT and OWT. According to this consortium, a WT is considered as a 'System' that is hierarchically bifurcated into 'Subsystems', 'Assemblies', 'Subassemblies' and 'Components'. This concept is shown in Figure 2.2 and an abridged list of 'Subsystems', 'Assemblies', 'Subassemblies' and 'Components' in a WT is given in Table 2.1. The diversity of components is evident from Table 2.1 where many electrical, electronic, mechanical and electromechanical are seen to build a WT.

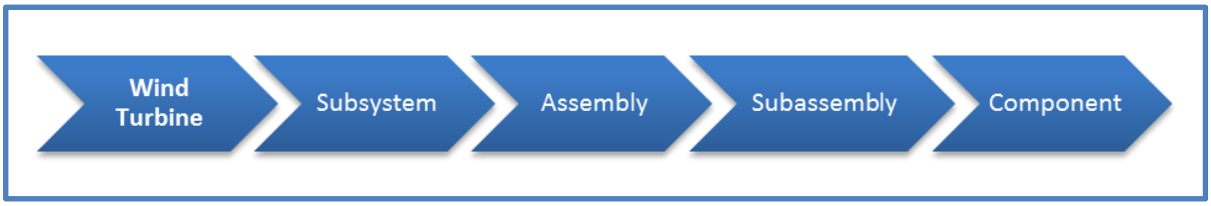


Figure 2.2 Shows hierarchical breakdown of a wind turbine to its component level

SYSTEM			
Wind Turbine			
SUBSYSTEMS	**ASSEMBLIES**	**SUBASSEMBLIES**	**COMPONENTS**
Drive Train	Gearbox	Bearing	Hose, Pump, Radiator, Thermostat, Motor
Module	Generator	Cooling System	Bushing, Case, Mounting, Torque Arm
	Main Shaft Set	Lubrication System	Filter, Debris/Level/Pressure/Temp Sensor
Electrical Module	Auxiliary Electrical System	Metrological / Nacelle/ other	Fan, Resistance Controller, Lamination
		Sensors	
	Control & Communication System	Rotor / Stator	Slip Ring, Encoder, Wattmeter, Magnet
Nacelle Module	Frequency Converter	Structural & Mechanical	Coupling, Rotor Lock, Shaft, Transformer
	Power Electrical System	High / Low Speed Side	High speed / position sensor, Fan, Fuse
Rotor Module	Hydraulic System	Mechanical Brake	Relay, Switch, Power Point, Pushbutton
	Nacelle Auxiliary	Electrical Services	Space Heater, Surge Arrester, UPS
	Yaw System	Lightening Protection System	Circuit Breaker, Cable, Analogue Digital
Support Structure			I/O
	Blade	Ancillary Equipment	Data logger, Protocol Adapter Card, CPU
Collection	Pitch System	Communication System	Watch Dog Unit, Control Software
System	Foundation	Condition Monitoring System	Power / Vibration / Watch Dog Switches
	Tower	Controller Hardware / Software	Cabinet, capacitor, Inductor, Converter
Metrological	HVDC/HVAC Cables	Safety Chain / System	Load Switch, Common Mode Filter
System	Grid Connections	Converter Auxiliary	Chopper, Ta, Tv, Cables, Contactor
		Converter Power Bus	Bus bars, Isolators, Soft Start electronics
		Power Conditioning / Circuit	Pressure Valve, Limit Switches, Linkages
Substation		Hydraulic Power Pack	Position Controller, Proportional valve
		Actuator	Anemometer, Wind Vane, yaw Encoder
		Yaw Brake / Yaw Drive / Yaw	Beacon, Fall arrester, Firefighting system,
		Sensor	
		Pitch Cabinet / Drive/ Sensor	Service Crane, Nuts & Bolts, Fibreglass
		Gravity Based Foundation	Yaw Break, Yaw Gearbox / Motor, Counter
		Tower	Lightening Protection, Hatch, Voltmeter
		Substation Transformer	Concrete, Steel, Corrosion Protection etc.

Table 2.1 Shows an abridged list of wind turbine components
(Source: EU FP7 ReliaWind Consortium)

The EU FP7 ReliaWind Consortium proposed over 250 generic components in a generic WT. However if each of these components was to fail in 5 different ways due to 5 different reasons, it results in 6250 cases for failure analysis. Moreover if such failures were analysed on 20 parameters, it will result in over 125,000 data fields. In order to limit the large number of cases of failures, this work identifies critical assemblies in OWT that have been termed as the Cost and Operation Critical Assemblies (COCA) for OWT (OWT-COCA). Although failures can be analysed at the Hardware Level or the Functional Level however, a Hardware Level Failure Analysis (HLFA) is only possible in association with component designers and manufacturers while a Function Level Failure Analysis (FLFA) can be performed by studying failures in the functionality of components. As a result in this work, FLFA of WT components is used.

2.4. Cost and Operation Critical Assemblies of OWT

This section identifies COCA for OWT using criterions like (i) maintenance cost, (ii) spares cost, (iii) failure downtime, (iv) failure frequency and, (v) criticality in operation. The key benefit of identifying OWT-COCA is that their maintenance can be prioritised to yield maximum benefits. However such identification will also optimise inventory for spares requirement that will reduce downtime and avoid maintenance delays and so optimise OWT maintenance. In Table 2.2, 12 of the 16 assemblies identified by EU FP7 ReliaWind Consortium for generic WT, have been compared from OWT perspective. A comparison of the various categories in Table 2.2 shows that the Gearbox and Generator are more critical for the operation of OWT than other assemblies. As a result in this work, Gearbox and Generator will be considered to be the OWT-COCA[II].

[II] The categorisation is done based on study of wind turbine journals, reports and experiments like Rademakers (2003) and Andrawus (2008).

Parameter / Assembly	Maintenance Cost	Spares Cost	Failure Downtime	Failure Frequency	Critical for Operation
Gearbox	Very High	Very High	Very High	Medium	Very High
Generator	Very High	Medium	Very High	High	Very High
Main Shaft Set	High	High	High	Low	Very High
Auxiliary Electrical Sys.	Medium	Low	Low	Very High	Medium
Control & Communication	Low	Low	Low	Low	Very High
Frequency Converter	Medium	Low	Low	Low	High
Power Electrical System	Low	Low	Low	High	Medium
Hydraulic System	Low	Low	Low	Medium	Low
Nacelle Auxiliary	High	Medium	Medium	Low	Medium
Yaw System	High	High	High	Low	High
Blade	Very High	Very High	Very High	Medium	Very High
Pitch System	High	High	High	Low	High

Table 2.2 Shows comparison of various parameters of wind turbine assemblies

A study by Quail and McMillan (2012) shows that the Gearbox and Generator have the highest downtimes as compared to other assemblies of WT. It is shown in Figure 2.3. This results conforms to the result shown in Table 2.2 where the downtime of Gearbox and Generator were identified to be Very High.

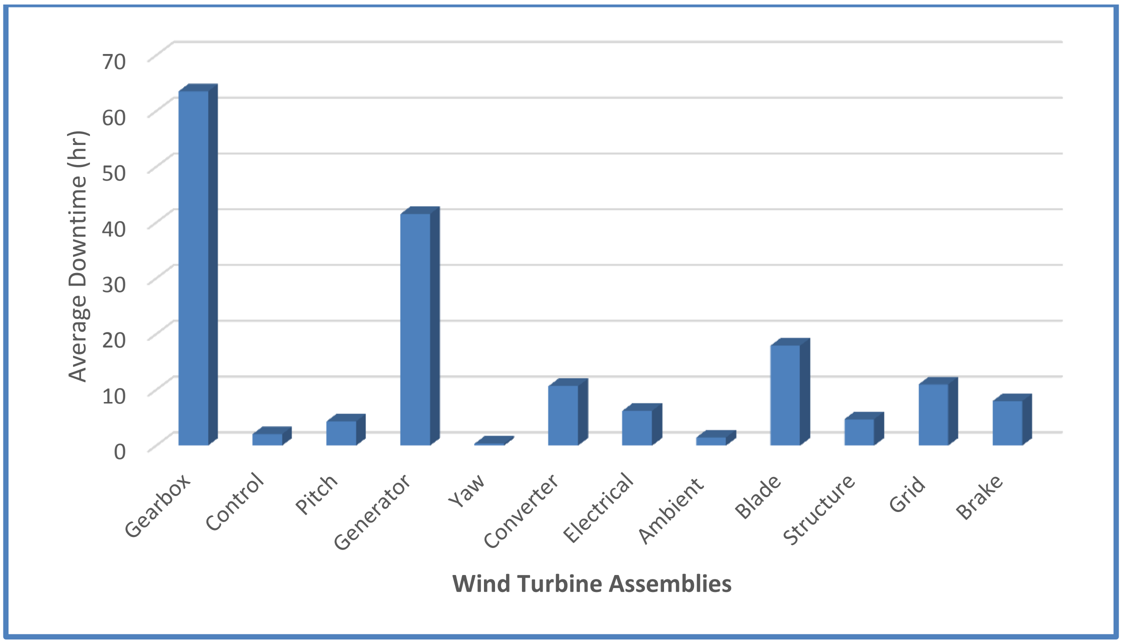


Figure 2.3 Plot of wind turbine assemblies and their average downtime (Source: Quail and McMillan, 2012)

However industry experiences vary as are seen from Figure 2.4 and Figure 2.5. Whereas the experience from Swedish Wind Farm (Figure 2.4) shows that maximum downtime was caused by gears, control system and electric systems, the frequency of failures in blade/pitch system, electric system, control system, sensors and hydraulics were more frequent than Gearbox and Generator.

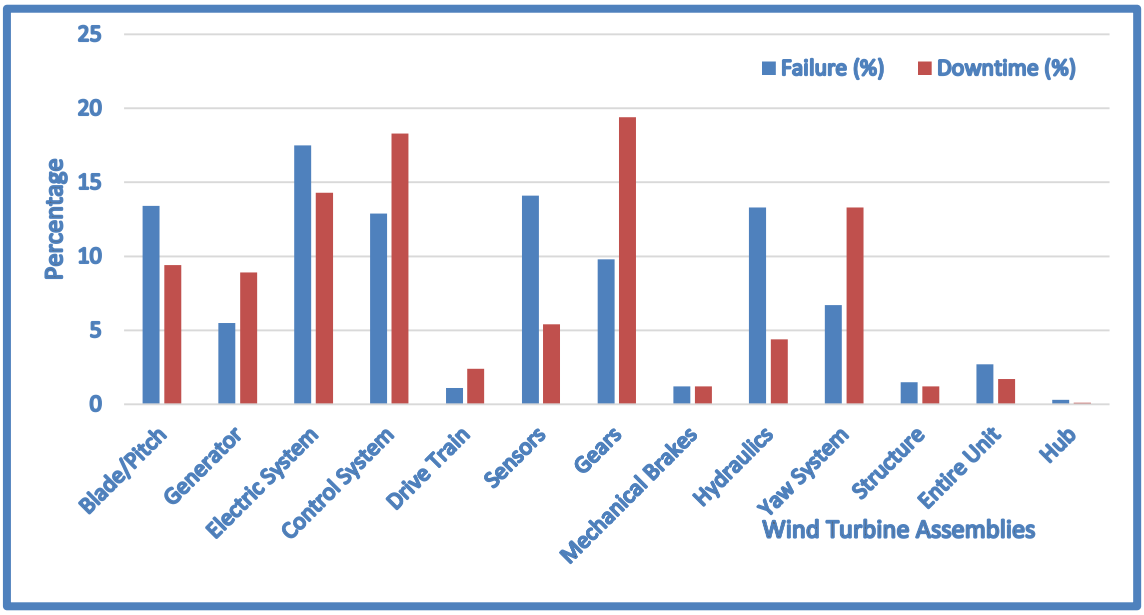


Figure 2.4 Plot of the percentage failure and percentage downtime of Swedish wind turbines during 2000-2004 (Source: Ribrant and Bertling, 2007)

Likewise in Figure 2.5, the failure rate and downtime of WT assemblies are seen to vary for European wind farms. Whereas the annual failure frequency were highest for the Electrical System and the Electrical Control, the highest downtime was seen to vary but primarily remained high for rotor blades, gearbox and drive train across different wind farms.

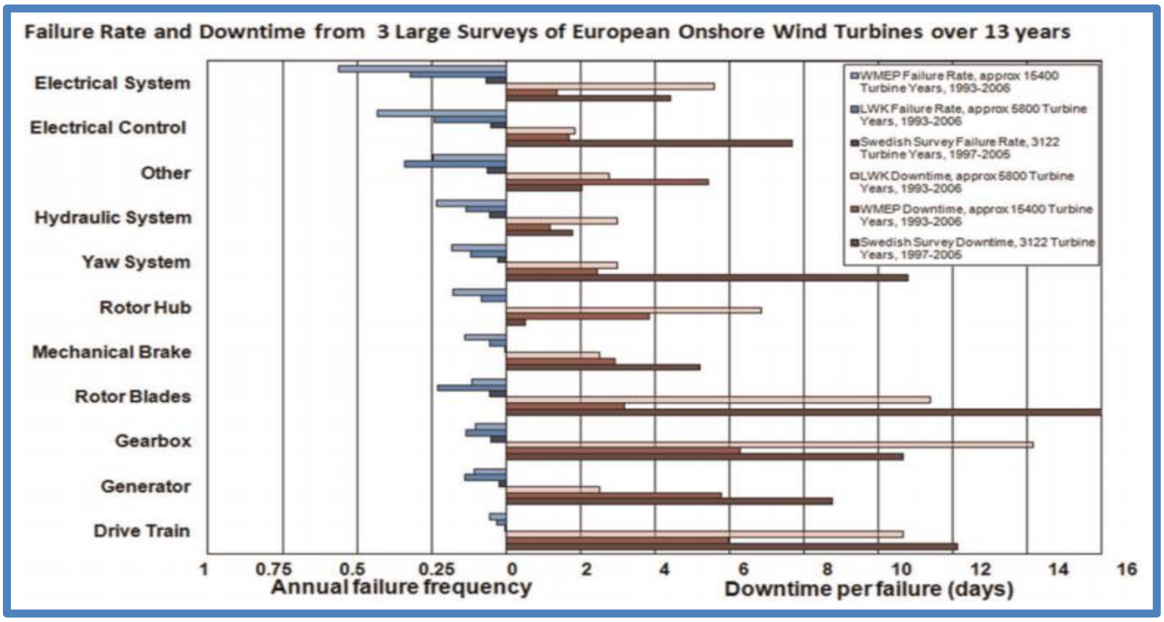


Figure 2.5 Plot of Failure/Wind Turbine/Year and downtime results for 25322 wind turbine year (Source: Chen, Matthews and Tavner, 2014)

Although Figure 2.3, Figure 2.4 and Figure 2.5 show varied industry experiences, a comparison of these results alongside the five criteria listed in Table 2.2 shows that Gearbox and Generator can be regarded as the COCA of OWT. However in view of the fact that electrical/electronic/sensor systems related failures exhibit high frequency of occurrence, and as the cumulative cost of frequent offshore maintenance is significant, it is essential that electrical system based failures are also identified as critical for OWT maintenance. As a result Gearbox, Generator and the Electrical System are considered to be the COCA for OWT in this work.

2.5. Detecting Failures in OWT-COCA

In order to identify failures/faults in WT components, it is required that failure detection methods are used. These methods should have fast response time, detect failures with high reliability, tolerate effects of failure and extricate failure signals from the background noise (Willsky, 1976; Massoumnia, Verghese and Willsky, 1989; Gertler, 1988; Murray, Hughes and Kreutz, 2005). If failure detection methods used for WT exhibit the above properties, it will improve the accuracy of failure detection and invariably result in better maintenance. In Table 2.3 some generic failure detection methods used for OWT-COCA are listed.

COCA	Failure Detection Method	COCA	Failure Detection Method	COCA	Failure Detection Method
Gearbox	Offline Oil Analysis	Electrical System	Cable Twist Sensors Status	Generator	Visual Inspection
	Component Replacement		Visual Inspection		Oil Analysis of Generator Bearing
	Online Oil Examination		Observation of Electrical Effects		Temperature Monitoring
	Temperature Monitoring		Component Replacement		Component Replacement
	Vibration Monitoring		Variation in Performance Parameter		Variation in Performance Parameter
	Visual Inspection		Measurement of Outputs		Vibration Monitoring
	Variation in Performance Parameter		Process Parameter Variation Technique		Vibration Monitoring of Bearing
	Accelerometer Technique		Thermograph Technique		

Table 2.3 Lists some common failure detection methods for OWT-COCA

(Source: Amirat, et. al., 2010; Al-Ahmar, Benbouzid, Amirat, Benelghali, 2008; Amirat, Choqueuse, Benbouzid, 2010; Amirat, et. al., 2009; Echavarria, Tomiyama, Hubert, Bussel, 2008;Guo and Wu, 2010; Cusido, et. al., 2008; Stack, Harley and Habetler, 2004)

However any single failure detection method is not able to detect all types of failures. For example vibration analysis can detect cracks and misalignment but not corrosion and erosion in gearbox components. Likewise a study of suspended particles in lubricating oil analysis can identifies corrosion/erosion but not cracks and misalignments. As a result a variety of failure detection methods are used for detecting failures in WT assemblies and components. But an OWT contains >10,000 components and so will require thousands of failure detection methods that will add to the lifetime cost of OWT. So there is a need to develop tools and analytical methods using which failures and faults could be easily identified in OWT components without using so many failure detection methods.

2.6. Maintenance Optimisation using Reliability Databases

Reliability is defined as the likelihood of a component to perform its intended function for a given period of time under given conditions without observing failure (Aggarwal, 2012). Manufacturers usually test components in controlled conditions and so when components are used in stochastic conditions their reliability of operation changes. This change in reliability value increases a component's propensity towards failure and need for maintenance. So reliability studies are useful to plan maintenance and have monetary impact (Langseth, Haugen and Sandtorv, 1998). Many industries have developed reliability databases that assist develop better components, predict failures and economise maintenance costs. Some of these reliability databases are listed in Table 2.4. These databases are occasionally reflections of the learning outcome of maintenance personal and so have practical relevance. Such studies make use of the mathematical formula of standard distribution patterns like Normal distribution, Weibull distribution and Exponential distribution, whose pattern co-resemble to characterise the failure pattern, to predict failure in components.

Database	Aspects Covered	Developed By
MIL-HDBK-217F	Electronic Components	US Military
FIDES	Electronic Components	French International Defence Companies
EPRD-97	Electronic Components	Electronic Parts Reliability
NPRD-95	Electrical, Electromechanical, Mechanical Components	Non Electronic Parts Reliability
PDS Data Handbook	Control and Safety Systems, sensors, valves, control logic	
FARADIP III	Electrical, electronic, mechanical, pneumatic, instrumentation, protective devices	Failure Rate Data in Perspective
IEEE 493-1997	Electrical power distribution systems	Institution of Engineers and Technology (IET)
Sintef Reports	Offshore upstream systems and its components	SINTEF
SubseaMaster	Subsea systems and its components	ExproSoft
WellMaster	Well completion equipment	SINTEF
RAC-DSC	All types of components	Reliability Analysis Centre
INSC	Nuclear plant systems and its components, material properties as useful for light water reactors	International Nuclear Safety Centre
RAM / SHIPNET	Marine machinery used on vessels	Worldwide Maritime Organisations
OREDA	All types of systems and components that are used by the Oil and Gas companies	Offshore Reliability Database
REMAIN	All systems used by railways across Europe	Commission of the European Communities, Directorate General of Transport

Table 2.4 Reliability databases of some focused industries

(Sources: Frequencies, 2010; Datsi.fi.upm.es, 2016)

2.7. Reliability Block Diagram (RBD)

A Reliability Block Diagram (RBD) is often used to find the reliability of WT if the reliability of WT subsystems, assemblies, subassemblies and components are known (Tavner, 2012). This is done using the concept shown in Figure 2.6. If 'M' denotes reliability, the reliability of series and parallel connected modules are obtained using Equation 2.1 (Figure 2.6 (a)) and Equation 2.2 (Figure 2.6 (b)).

$$AM_{Series} = \prod_{i=1}^{n} M_i = M_1 * M_2 * M_3 \quad \textbf{(2.1)}$$

$$AM_{Parallel} = \sum_{i=1}^{n} M_i = M_4 + M_5 + M_6 \quad \textbf{(2.2)}$$

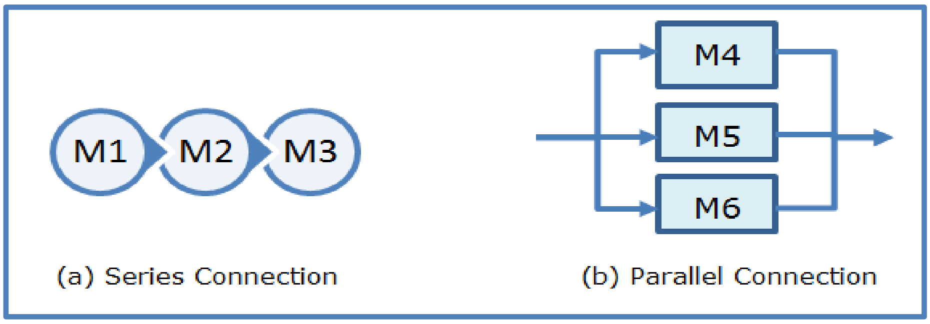


Figure 2.6 Shows reliability calculation for (a) series and (b) parallel connected modules

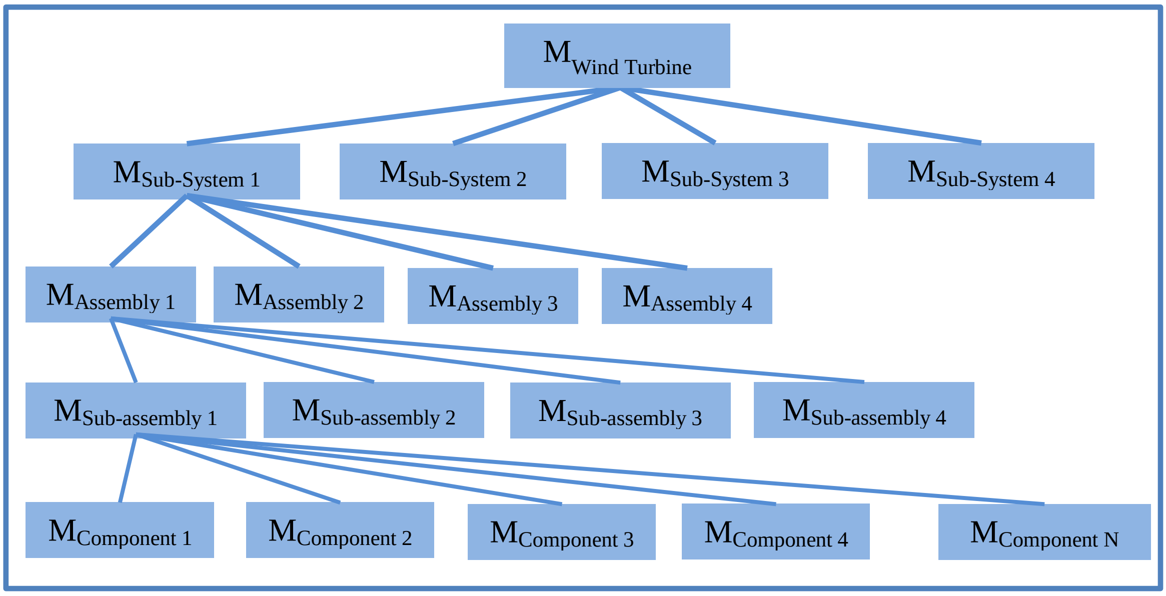


Figure 2.7 Shows the hierarchical method for evaluating the reliability of a WT (M = Reliability)

If a WT is modelled as series and parallel connected subsystems, assemblies, subassemblies and components as shown in Figure 2.7, the reliability of WT can be calculated using Equation 2.3 – 2.6. In these equations the notation $\sum\prod\langle M_i|M_j\rangle$ is used to denote the result obtained by calculating the overall reliability of series and parallel connected units at the subsystems, assemblies, subassemblies and components levels.

$$Reliability_{Sub-assembly} = \sum\prod\langle M_i|M_j\rangle_{Component} \quad \textbf{(2.3)}$$

$$Reliability_{Assembly} = \sum\prod\langle M_i|M_j\rangle_{Sub\ Assembly} \quad \textbf{(2.4)}$$

$$Reliability_{Sub-system} = \sum\prod\langle M_i|M_j\rangle_{Assembly} \quad \textbf{(2.5)}$$

$$Reliability_{System\ (WT)} = \sum\prod\langle M_i|M_j\rangle_{Sub\ System} \quad \textbf{(2.6)}$$

The utility of RBD was shown in the design of an optimal maintenance scheme using Reliability Centred Maintenance (RCM) (Andrawus, 2008). But use of RBD in WT has limitations as it needs reliability values of all components (that is not easy to obtain), it requires a tool to calculate reliability values at all levels of WT and reliability value of feedback circuits cannot be obtained using a RBD model. It also does not indicate nature of failure that is critical to plan WT maintenance.

2.8. Compensatory Provisions

Although RBD method was seen to have limitation in Section 2.7, it can be used to analyse the usefulness of implementing series and parallel compensatory provisions in WT assemblies and components. In this work a compensatory provision is defined as a sacrificial component that when connected alongside the original protected component will improve the overall reliability of WT. The concept of using series compensation and parallel compensation are shown in Figure 2.8. The two types of compensations have their own advantages like

- *Series Compensation*: a sacrificial component connected in series will fail prior to any damage being induced in the protected component
- *Parallel Compensation*: a duplicate component will act as a standby and take over the role of the original component if the original component was to fail

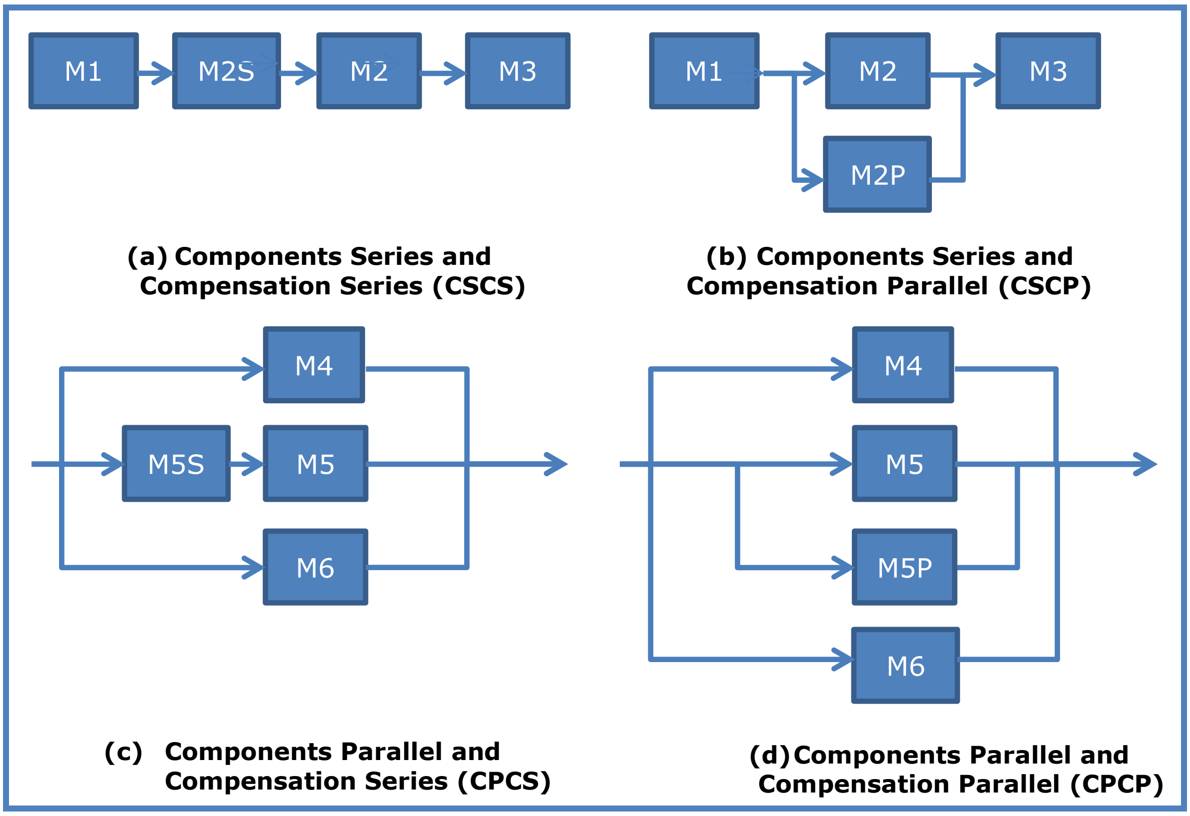


Figure 2.8 Shows different configurations for implementing compensatory provisions (M2S, M5S = series compensations, M2P, M5P = parallel compensations)

A reliability based analysis of the series and parallel compensatory provisions shows that the overall reliability of the system is improved by including series and parallel compensatory provisions. This is shown below in Case 1 – Case 4.

Case 1: CSCS: $\Delta \boldsymbol{Reliability} = \boldsymbol{M_1} * \boldsymbol{M_2} * \boldsymbol{M_3} - \boldsymbol{M_1} * (\boldsymbol{M_{2S}} * \boldsymbol{M_2}) * \boldsymbol{M_3} = \boldsymbol{M_1} * (\mathbf{1} - \boldsymbol{M_{2S}}) * \boldsymbol{M_2} * \boldsymbol{M_3}$

Case 2: CSCP: $\Delta \boldsymbol{Reliability} = [\boldsymbol{M_1} * (\boldsymbol{M_2} + \boldsymbol{M_{2P}}) * \boldsymbol{M_3}] - \boldsymbol{M_1} * \boldsymbol{M_2} * \boldsymbol{M_3} = \boldsymbol{M_1} * \boldsymbol{M_3} * \boldsymbol{M_{2P}}$

Case 3: CPCS: $\Delta \boldsymbol{Reliability} = [\boldsymbol{M_4} + \boldsymbol{M_5} + \boldsymbol{M_6}] - [\boldsymbol{M_4} + (\boldsymbol{M_{5S}} * \boldsymbol{M_2}) + \boldsymbol{M_6}] = \boldsymbol{M_5} * (1 - \boldsymbol{M_{5S}})$

Case 4: CPCP: $\Delta \boldsymbol{Reliability} = [\boldsymbol{M_4} + (\boldsymbol{M_5} + \boldsymbol{M_{5P}}) + \boldsymbol{M_6}] - [\boldsymbol{M_4} + \boldsymbol{M_5} + \boldsymbol{M_6}] = \boldsymbol{M_{5P}}$

2.9. Methods to Analyse Failures

A drawback of RBD method (Section 2.7) was that it provided a numerical value for the wellness of a component (/reliability) but did not provide any information about the nature of failure in the component. Such information is critical for preplanning maintenance activities and has financial impact. However methods exist that can provide such information like Cause Consequence Analysis, Failure Checklist, Event Tree Analysis, Failure Modes & Effects Analysis (FMEA), Criticality Analysis (CA), Fault Tree Analysis, Hazard & Operability Analysis, Reliability Analysis and What-If Analysis (Guo and Wu, 2010). However amongst these methods, FMEA and CA, together known as FMECA, is a scalable and highly structured method to analyse and determine the consequences of failures (Chandler, Denson, Rossi and Wanner, 1991). This method also offers the flexibility of using qualitative and quantitative approaches to analyse failures when supporting failure data may or may not be available respectively. This is important from OWT perspective where failure analysis is required but failure data may not be readily available.

Although there are many standards for performing FMECA, like the MIL-STD 1629, IEC 60812, BS 5760-5 and SAE J1739 (Rausand, 2005), this work uses the fundamental concept of evaluating FMEA and CA in order to perform FMECA.

This process is shown in Figure 2.9. The process for doing FMECA starts by performing FMEA by making a component level block diagram of the machine, identifying their failures, identifying their root causes and identifying their effect and failure resolution methods. The CA makes use of qualitative and quantitative methods to determine the criticality of failure and component.

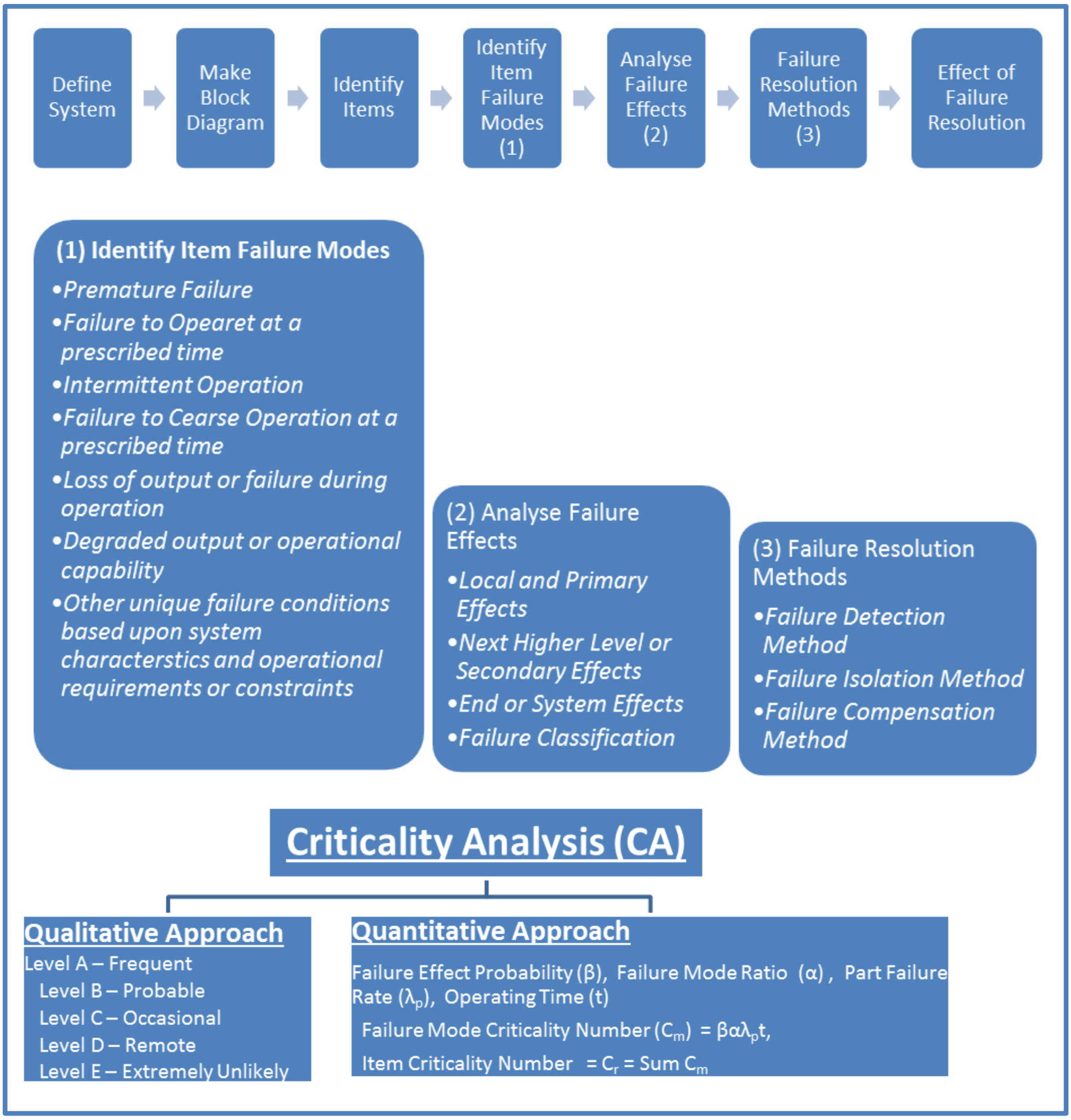


Figure 2.9 Shows the standard process for doing FMEA and CA

When using the qualitative approach, the Risk Priority Number (RPN) is often calculated to rank failures. The RPN value is calculated by multiplying the value of Severity, frequency of Occurrence and ease of Detection (S,O,D) of a failure. This is shown in Equation 2.7.

$$Risk\ Priority\ Number = Severity * Occurance * Detection \qquad \textbf{(2.7)}$$

The values of (S,O,D) for failures is usually chosen from a 10 point scale where the value of Severity, Occurrence and Detection (S,O,D) is allocated a value from 1 – 10 (Table 2.5). So for a failure that has Severity as 'Moderate Effect causing return of product', Occurrence as 'Frequent' and Detection as 'Moderate', its RPN value will be 140 (= 5*7*4). Likewise for (S,O,D) values of (4,3,6) and (6,3,9) the RPN values will be 72 and 162 respectively.

Rating	Severity (S)	Occurrence (O)		Detection (D)
		Probability	Description	
1	Effect is not noticed	$< 10^{-5}$	Extremely Less	Certain
2	Very slight effect noticed	10^{-5}	Remote	Very high
3	Slight effect causing annoyance	10^{-5}	Very Slight	High
4	Slight effect causing return of product	$4 * 10^{-4}$	Slight	Moderate
5	Moderate Effect causing return of product	$2 * 10^{-3}$	Occasional	Medium
6	Significant Effect	$1 * 10^{-2}$	Moderate	Low Chance
7	Major Effect	$4 * 10^{-2}$	Frequent	Slight
8	Extreme Effect, system inoperable, safety issue	0.20	High	Remote
9	Critical Effect, System shutdown, Safety risk	0.33	Very High	Very Remote
10	Hazardous, Without warning, life threatening	>=0.5	Extremely High	No Chance, no inspection

Table 2.5 A 10 point scale for determining values of Severity, Occurrence and Detection

However not all industries make use of the 10 point scale as shown in Table 2.5 and use of 5, 6 and 8 point scales are not uncommon. However such choices result in varied RPN values that results in confusion while planning maintenance. So a more consistent system to rank failures need to be developed according to the requirements of OWT maintenance.

The confusion caused by varied RPN value can result in maintenance error. However this is just avenue that can result in maintenance error and so require costly re-maintenance activities. There is a need to identify such sources of error and develop processes to overcome their occurrence. One such error, human errors in maintenance (Dhillon and Liu, 2006), is discussed in the next section.

2.10.Human Fallacy

Errors caused by humans during planning and execution of maintenance can result in failure of a planned maintenance and/or costly maintenance reworks. These errors are caused by several reasons some of which are listed in Table 2.6. As seen from Table 2.6, errors can be caused by manpower, supervisor, support infrastructure, management decisions and the overall maintenance management.

Avenue	Potential Shortfall
Job Instructions / Description	Vague or incomplete job description
Background Engineering Support	Maintenance solely managed by labour
Standards	Personal experience and skillset given priority
Need to Revise Work	Job requires reworking or not completed timely
Dealing with Old Machines	Maintenance guidelines not available, possible use of hit and trial method
Planning of Maintenance	Unskilful maintenance management by workers
Complex Maintenance Activity	Requires management of many time bound jobs
Workload	Not enough manpower, excessive workload on available resource
Communication	Required meetings, etc. not taking place
Management of Maintenance	Skillset to manage maintenance not available
Preplanning of Works	Occasionally work is not pre-planned
Awareness of Maintenance Methods and Processes	Manpower not made aware of required maintenance methods and processes
Changes Made to Plan	Occasional change in maintenance plans
Use of Tools / Instruments	Not skilled to use required tools and instruments
Scope of Repetitive Work	Taken for granted, possibly left unplanned
Skillset of Workers	Proper training not provided as required
Supervisors	Proper control mechanisms not put in place
Labour Issues	Manpower is not considered in decision making
Working Environment	Not suitable for professional growth, issues with interaction, etc.
Time Management	More than expected time taken to complete work
Scope of Future Work	Scope of future works are not well documented or are not professionally managed
Reporting System	Guidelines for reporting are vague and frequent loss of information occurs
Interrupted Jobs	Many works done simultaneously result in delays

Table 2.6 Lists potential shortfalls that result in human fallacies during maintenance works

However the above issues are resolved if planning and management of maintenance are brought under the framework of project management and not leaving it at the discretion of the service crew. Use of project management in maintenance will clearly define the scope of each maintenance work, establish realistic timelines, identify constraints and make plans for effective maintenance. It will also effectively manage the skillsets of workers and supervisors, improve communication between businesses and advance use of standard maintenance practices. It can also plan complex sequential maintenance works that are critical for offshore maintenance and so is recommended for use in OWT maintenance.

2.11.Principle of Optimisation

Optimisation is a mathematical process wherein a set of variables are varied under constraints to maximise or minimise the value of an objective function (Nocedal, 2006). It is represented as,

Minimise (/**Maximise**) $f_0(x)$

Subject to $f_i(x) <= b_i$, i = 1,2,3,…..,m

where,

$x = (x_1, x_2, x_3, x_4, \ldots\ldots x_n)$: variables to be optimised

$f_0 : R^n \text{->} R$: Objective Function that needs optimisation

$f_i : R^n \text{->} R$, i = 1,2,3,…m : Constraint Functions

Optimisation ensures that the best value of an objective function is obtained for given constraints (/conditions). However success of optimised solutions, when applied practically, have been <10% (Rethinking Cost Structure - KPMG, 2007). This has been since optimisation does not offer the flexibility and variability which is observed in practical scenarios. As a result if mathematical optimisation is done to maximise profits or minimise the LCoE of OWT, chances of its success in practical application is minimal. Instead, if the overall challenges associated with OWT maintenance are (i) reduced to smaller challenges, (ii) suitable flexibility is allowed in the values of parameter, and (iii) optimisation is done on a case by case basis, chances of its success will increase. However this requires identification of cost intensive avenues in OWT maintenance and maintenance performance parameters which then needs to be streamlined and optimised.

Industry experiences vary for cost intensive avenues in OWT maintenance. However from a practical viewpoint some cost intensive areas in OWT maintenance have been identified as: onshore logistics (like port side activities, warehouses), offshore logistics (like workboats, helicopters, jack up services), back office administration, OWT maintenance (manpower, spares) and maintenance of export cable, grid, array cable and foundation (Hassan, 2013). From the perspective of optimising OWT maintenance, based on maintenance performance parameters (Wireman, 2005), some avenues that require maximisation/minimisations have been identified and listed in Figure 2.10

Performance Parameters (Maintenance)

Parameters for Maximisation	*Parameters for Minimisation*
1. Asset Utilisation	1. Levelised Cost of Energy
2. Availability	2. Maintenance Cost
3. Capital Equipment Life	3. Direct and Indirect Costs
4. Customer Satisfaction	4. Resource Requirement
5. Reliability	5. Downtime
6. Safety	6. Opportunity Cost
7. Maintenance Records	7. Injuries
8. Return on Net Asset	8. Inventory

Figure 2.10 Lists key performance parameters of optimisation for OWT maintenance

However, any work on mathematical optimisation of OWT maintenance using cost intensive avenues or maintenance performance parameters is complex due to interdependencies that these parameters have amongst themselves and other variables which may be stochastic in nature. Like work on maximisation of reliability/availability of OWT requires dealing with stochastic offshore weather. Likewise since OWT maintenance is an international business (OWT owners, service providers, component manufactures/distributors may be located in different countries), work on minimisation of direct/indirect costs will depend on the stochastic currency exchange rates. As such the result of optimisation works in these cases will fluctuate with time and vary on a case by case basis. The use of industry standard strategies like keeping many hot swappable parts (parts that can be exchanged with faulty parts without switching off the machine) or waiting for long periods of time to service several failures at one time, may not be cost effective at all times. Similarly maintaining a strong supply chain to reduce downtime (Roux, 2013) may/may not be economical (Cost Optimisation, 2009). So, any work on mathematical optimisation of OWT maintenance maybe counterproductive and requires new perceptions like the use of predictive CBM.

2.12. Health & Safety of offshore workers

Maintenance of OWT involves working at heights (>80m), in depths, with high electrical power, in humid conditions, in confined spaces, with rotating machines and require long offshore travels. All such works pose safety hazards for which the UK's Health, Safety and Environment (HSE) Agency (HSE, 2016) and other similar agencies in different parts of the world have regulations. The existing regulations require organisations to minimise the risk of hazards and accidents for offshore crew by incorporate appropriate safety norms. Although existing regulations are designed according to the need of Oil & Gas and Marine industry, the hazards encountered in performing OWT maintenance works are unique as operating heavy rotating machinery in offshore locations is a new technology. It is hence required that further work is done to identify hazards associated with OWT maintenance and put processes to minimise their risks.

2.13.Optimisation of Spares Inventory

In Section 2.11 warehouse cost (cost of spares inventory) was identified to be one of the cost intensive avenues in OWT maintenance. There is limited information in the public domain about optimisation of spares inventory or spares management for OWT. In a work by Tracht et. al. (2013), where they designed an optimal spares inventory for OWT under the restrictive conditions of accessibility and resource availability, the quantitative method used involves many variables whose values are not only difficult to obtain but its practical implementation is complex and not possible without supportive tool.

However several simpler theories have been used in industries to optimise spares inventory but their application in OWT inventory control is not known. This includes techniques where maximum/minimum stock level is maintained at all times and a re-order is placed when the number of spares fall below a critical level. Other techniques include maintaining an Economic Ordering Quantity (EOQ) (Goyal, 1985), Average of Stock Level (Hill, 1997), ABC Analysis (Flores and Clay, 1986), Just in Time (Hutchins, 1999) and Material Required Planning (MRP) (Whybark and Williams, 1976). But the challenges associated with OWT are unique and requires a redesign of the above techniques if they are to be used to optimise the spares inventory for OWT. This is as: (i) forecasting spares requirement is difficult due to the limited ability to forecast failures in OWT components, (ii) with >10,000 components in OWT, the need to maintain adequate stock of so many components is a cost intensive work, (iii) the availability and cost of WT spares fluctuates due to demand and supply, (iv) the evolutionary nature of OWT requires that both traditional and improved models of components are stored and so incur higher cost to manage inventory, (v) the cost for maintaining 10,000 of spares for long durations of time (if unconsumed) will be very high, and (vi) the lead time to procure specialist or scarce spares is high. However the penalty for OWT downtime is also very high that prompts service providers to hold majority of the spares for long intervals of time even if not used. This invariably increases the overall cost of WT maintenance.

But the EOQ model is capable of determining an optimal stock level under conditions of known and uncertain demands (Silver, 1976) however this model does not differentiate between critical and non-critical components and so will require storage of all types of components at all times. This deficiency is overcome in ABC Analysis (Proportional Value Analysis) where spares are grouped according to their monetary value and frequency of consumption in High Value (A), Medium Value (B) and Low Value (C). The above techniques partially overcome the limitation of maintaining many spares, as a minimum stock of all critical and non-critical components are still required in the inventory at all times even if they are not used, there is a need to make proactive decisions on spares.

In view of the benefits offered by EOQ and ABC models, along with the need to make prudent decisions to order spares on a proactive basis, this work proposes use of an OWT Sparesholding model to optimise the spares inventory for OWT. This model is shown in Figure 2.11.

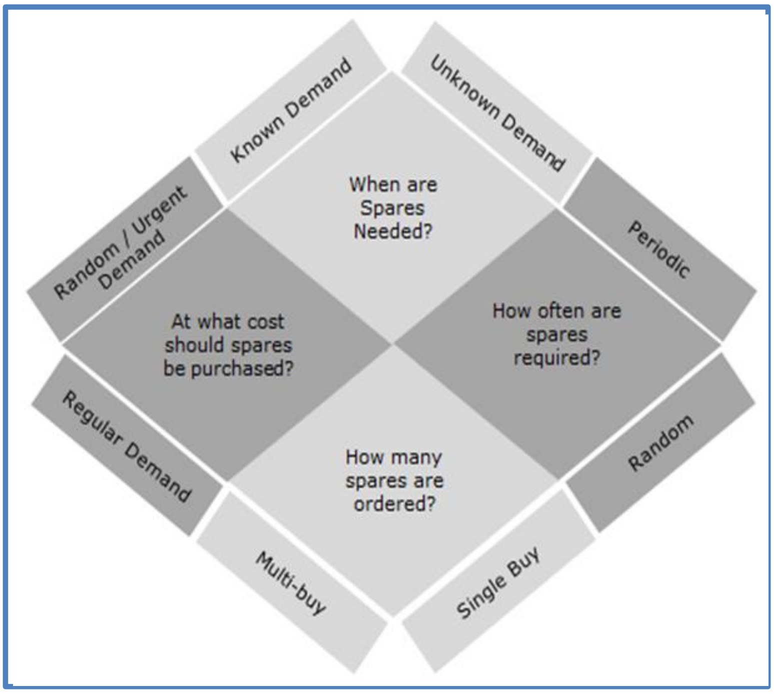


Figure 2.11 Proposed model of an Optimal Inventory Management System for OWT

The model shown in Figure 2.11 is based on some key questions that an inventory manager would ask while economising the spares inventory. These questions are "When are spares needed?", "How often are these spares required?", "How many should be ordered?", and "At what frequency should the spares be ordered?". Although a complete mathematical analysis of the model given in Figure 2.11 is outside the scope of this work, some of its advantages are (i) the answer to the question "When are spares needed?" under the constraint of known and unknown demands can be found using the EOQ model, (ii) the answer to the question "How often are spares required?" under the constraint of periodic and random demands can be found using the ABC model, (iii) the answer to the question "How many spares are ordered?" under the constraint of single-buy and multi-buy can again be found using the ABC model, and (iv) the answer to the question, “At what cost should the spares be purchased?” under the constraint of random demand and regular demand can be found using EOQ and ABC models. However since consumables like hose, fuse, switch, lubricating oil and coolant, are required in every maintenance activity, an adequate stock of consumable items should be maintained in the inventory at all times. So any work on optimisation of OWT inventory should be focused on non-consumables.

2.14. Need for a Maintenance Optimisation Tool for OWT

Although many tools are available to monitor and estimate the power output from WT like WAsP, WindPRO and ANSYS (Moskalenko, Rudion and Orths, 2010) (Yong-Li and Jie, 2010), tools are required to support OWT maintenance. For example tools are required to detect failures from condition monitoring data (Becker and Poste, 2006; Rodriguez, et. al., 2008; Echavarria, Tomiyama, Huberts and Van Bussel, 2008), perform failure analysis, categorise failures, identify cost effective maintenance scheme, estimate cost of maintenance and compute maintenance performance parameters (Sinha, Steel, Andrawus and Gibson, 2013). Some tools have been developed to assist with WT maintenance however they have limited but focused scope. These include CONTOFAX, ECN Model, XFMEA, Reliability Workbench, Reliability Studio 2007(V2) and Dezide Wind Advisor (Van Bussel and Schontag, 1997; Wessel, Prins, Lok and Leunis, ; Publishing, 2016; Reliability Workbench, 2016; Relex 2007 Curriculum Guide, 2016). However a tool that can detect failures from condition monitoring data, analyse these failures and support plan maintenance will solve some of the key problems that OWT maintenance planners currently face. The prerequisites and scope of such a tool were listed by Sinha et. al. (2013). Such a tool should also be able to show the status of assemblies (Rademakers et. al., 2008; Anon, 2016) according to their condition monitoring data (Wei and Liu, 2010) and plan CBM for OWT, an economical alternative to existing random maintenance schemes. The tool should have ready reference to service manuals and installation guides (Sinha et. al., 2013) that will enable service crew to follow standard maintenance practices. However as technology is evolving, such tools should be developed on a platform that is compatibility with other prominent software/hardware platforms to enable easy migration of data and information (Birolini, 2014).

Although a tool developed to perform failure analysis using the condition monitoring data is useful to plan an economical maintenance scheme for OWT, its usefulness can be made more widespread by having modules that can anticipate OWT power (Kusiak, Zheng and Song, 2009b) based on forecasted wind speed (Tarek, Ehab and Magby, 2009) and uses latest condition monitoring techniques to identify failures/faults, like analysis of the frequency spectrum of electrical signals (Kusiak, Zheng and Song, 2009a), all on a single platform. Such tool should also be compatible to work alongside SCADA system so that condition monitoring data could be processed in real time for failures and faults. This will save time and cost linked to failure detection for OWT operators in addition to planning maintenance. This is important as such a tool will process 28,800 data entries each day per WT to identify failures and faults using SCADA data (calculated for maximum, minimum, average and standard deviation values for 50 monitored parameters generated every 10 min interval). For an offshore wind farm that contains 50 OWT, this equates to 1,440,000 data/day or 525 million data entries per year. A tool developed to detect failures and faults using SCADA system data will have a significant impact on economisation of OWT maintenance and is very much desirable. But the design and development of such a maintenance optimisation tool for OWT will be constrained by many technological and operational limitations as given next.

2.15. Database of Maintenance Optimisation Tool for OWT

The extent of data generated from SCADA system, condition monitoring of components, management of resources and results obtained from queries and analysis of data requires that the database, in which such data is stored, is robust, capable and reliable. Some prerequisites for selecting a database for building the Maintenance Optimisation Tool for OWT (OWT-MOT) were listed by Sinha et. al. (2013) and further discussed by Sinha and Steel (2015 (c)). However for easy reference, this is given in Table 2.7. As is seen from Table 2.7, the database selected for use in OWT-MOT should offer the facility of expansion, data migration and privacy, amongst other requirements. These are important as such data are critical from technical and financial perspective.

Requirements	Required Characteristics from Database Software
Large Volume of data	Condition Monitoring, SCADA systems very quickly generate gigabytes of data. Selected Database software should be able to support large volumes of data.
Relationship	Stored data would have relationship to each other hence the chosen database should be capable of simultaneously establishing and handling many relationships between data
Formats of Data	Incoming data are in various formats, hence database software should be able to support various formats of data, like integer, floating number, date, picture
User Interface	Software would be used by trained and unskilled personal, so its user interface need to be simple and easy to understand and navigate
Safety / Privacy	Since multiple users will logon to the database software simultaneously, hence viewing selected data need to be restricted by user authorisation
Reliability	Database should ensure that stored data does not become corrupt with time and hence facility should be there for both local and remote data backup
Commands	Common words enabled user interface would assist unskilled people easily interact with the database using the software tool.
Storage / Retrieval	The database software should have easy and short to remember commands that does not take appreciable time to execute to storage, manipulate or retrieve data
Expansion	With new modules, the size of database would increase. Hence the selected software should have a scalable architecture
Redundancy	Facility for identification, retrieval and archiving of long time unused, corrupt and unwanted data should be present. This is essential for housekeeping.
Protection of stored Data	Accidental deletion of related data should be avoided by the database software least it would form redundant sets of data
Access and Access Time	Database software should provide facility for efficient management of data so that data can be accessed in very short interval of time
Migration	Selected database should be compatible with other available databases so that in case of need, data can be transported between different types of databases

Table 2.7 Prerequisite for a database for use in OWT-MOT

(Source: Sinha and Steel (2015 (c))

However a prerequisite of such a database is that it should be able to store different formats of data (Table 2.7). This is important since condition monitoring data and other data can have different formats like pictures, comments, integer values and real values, amongst other. A database chosen to store such data will additionally be required to record monitory values in different currencies, date, time and comments in different languages (if applicable). Any database chosen for OWT-MOT purpose should be able to support such functionalities. In Table 2.8 the different data types have been listed.

Data Type	Comment
varchar	Variable width character string, maximum 8,000 characters
nchar	Fixed width Unicode string, maximum 4,000 characters
bit	Allows 0,1 or null
image	Variable width binary string. Maximum 2GB
smallint	Allows whole numbers, -32,768 and 32,767
int	Allows whole number between $-2.14*10^9$ and $2.14*10^9$
float	Floating precision number, $-1.79*10^{308}$ to $1.79*10^{308}$
money	Monetary data from $-922*10^{12}$ to $922*10^{12}$
real	Floating precision number data from $-3.4*10^{38}$ to $3.4*10^{38}$
date	Stored date only
time	Store a time only
timestamp	Stored unique number that gets updated every time a row is created/modified
xml	Stores xml formatted data. Maximum 2GB
varbinary	Variable width binary string. Maximum 2GB
datetimeoffset	Gives date and time

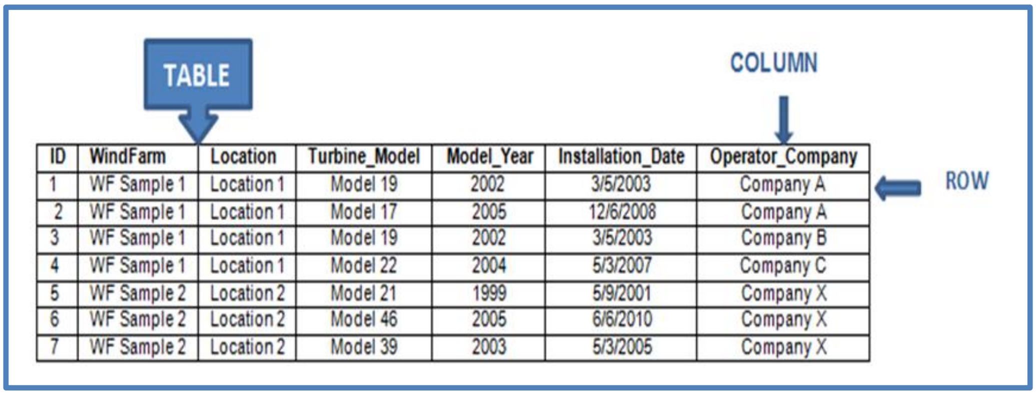
Table 2.8 Data Types and Variables used in the database[III,IV]

However modern database management software like SQL, Oracle and MySQL support multiple data types given in Table 2.8 and meet the requirements given in Table 2.7. In addition if data is arranged in the database using the relational database framework, a technique that is supported by SQL, Oracle and MySQL and other modern databases, the problem of managing large volumes of data can be overcome. This has been showed in work by Sinha and Steel (2015 (c)). In a relational database the data is stored in tables and the location of the data is obtained from the unique values of row and column numbers. In addition, standard commands exist to store and retrieve the data from relational database. An example of the tabular nature of a relational database has been given in Figure 2.12. An example of the result obtained from querying the relational database for the type of WT models in WF Sample 1 (Figure 2.12) is given below.

Command: ***SELECT*** *Turbine_Model* ***FROM*** *WindFarm Details* ***WHERE*** *WindFarm = 'WF Sample 1'*

Result: *Model 19, Model 17, Model 19, Model 22*

III http://www.w3schools.com/sql/sql_datatypes.asp
IV http://www.tutorialspoint.com/sql/sql-data-types.htm



ID	WindFarm	Location	Turbine_Model	Model_Year	Installation_Date	Operator_Company
1	WF Sample 1	Location 1	Model 19	2002	3/5/2003	Company A
2	WF Sample 1	Location 1	Model 17	2005	12/6/2008	Company A
3	WF Sample 1	Location 1	Model 19	2002	3/5/2003	Company B
4	WF Sample 1	Location 1	Model 22	2004	5/3/2007	Company C
5	WF Sample 2	Location 2	Model 21	1999	5/9/2001	Company X
6	WF Sample 2	Location 2	Model 46	2005	6/6/2010	Company X
7	WF Sample 2	Location 2	Model 39	2003	5/3/2005	Company X

Figure 2.12 Shows layout of a relational database where data are stored in rows and columns

2.16. Stakeholders of OWT Maintenance

Meeting stakeholder requirements is critical for the success of any business (Drienikova and Sakal, 2012). As a result businesses take stakeholders viewpoint when planning new strategies. This is also true for OWT maintenance business. In Table 2.9, stakeholders of OWT maintenance have been listed. This includes maintenance managers who plan work orders, see regulatory requirements and estimate costs, and Quality Control Manager who deal with quality issues relating to maintenance. So any tool developed for OWT maintenance should be dedicated towards meeting the requirements of its stakeholder. It is critical that OWT-MOT is designed to meet the organisational and stakeholders objectives else it will be unprofitable as witnessed in industries (Beard and Sumner, 2004).

Stakeholder	Requirement (Information)
Head of Department	Business Performance, Major Technical/Financial Issues
Business Development Manager	Overview of Financial and Technical information about OWT, Businesses prospects
Maintenance Manager	Maintenance Plan, Regulatory Compliance, Maintenance Cost, Manpower, Staff Training
Maintenance Engineer	Maintenance Plan, Quality, Service Feedback, Benchmarking
Maintenance Planner	Building and viewing Weekly, Monthly Work Schedules/work order/job description, reviewing maintenance records etc.
Service Crew	Job Description, Work Order, Feedback, Special Needs
Application Manager	Hardware and Software performance logs
Health & Safety Officer	Work Process, Identification and evaluation of Hazards, recommending precautions, safety appliances
Inventory Manager	Spares stock, orders, costs, proposed spares arrival time, etc.
Spares Vendors	Requisition, Order Number, Item requested, quantity, etc.
Third Party Service Providers	Description of work, work order particulars, etc.
Operations Manager	Availability of manpower, transport, instruments, tools etc.
Quality Control Manager	Feedback on maintenance, quality control, assessment of quality in work performed
Office Administration	Scheduling activities, maintenance of general log, activity logs
Finance Department	Costs, Budget approval, Payments, etc.

Table 2.9 Various stakeholders and their requirements from OWT-MOT

2.17. Summary

This chapter identified critical assemblies in OWT. It identified the need to design failure analysis and failure ranking methods based on OWT requirements. The chapter highlighted the constraints of using mathematical optimisation to optimise OWT maintenance and instead acknowledges use of alternate strategies like predictive CBM. A predictive CBM is a practically viable solution that will give direct cost reductions. Use of RBD in determining WT reliability was highlighted and it was applied to identify the usefulness of compensatory provisions.

A central theme identified across all sections in this chapter was the need for supportive tools to plan OWT maintenance. An immediate need was identified for a tool that could perform component level failure analysis for OWT components in order to plan CBM. Many advantages of such tool were identified including the benefit of predicting the nature of failure that is critical for planning resources. The requirements and prerequisites from such a tool were also noted. It was also identified that such tools should be designed to meet the requirements of its stakeholders.

However the design of a failure analysis tool requires study of the conditions that lead to failure in various WT components. This is shown in the next chapter where the role of condition monitoring in identifying root causes of failures is discussed and the importance of this strategy is highlighted.

CHAPTER 3. Condition Monitoring and design of a Prognostic CBM for OWT

3.1. Introduction

In Section 2.11 the limitations of mathematical optimisation were identified and an alternative method to economise OWT maintenance was identified in Predictive Condition Based Maintenance. A predictive maintenance is planned in anticipation of failure/faults and so reduces downtime, controls need for spares and prevents failures become catastrophic faults. Condition Monitoring (CM) is used to determine the health of machine components and is useful in identifying failures and faults. The CM methods are also useful in identifying potential root causes of failures that is useful in controlling the occurrence of failures in future. This chapter shows case studies of operational WT from which it is evident that CM is able to identify failure/faults in components and identify their root causes.

In Chapter 2 a need was identified to perform component level failure analysis for OWT if a CBM was to bring expected benefits. This chapter discusses about a modified format of FMECA to analyse failures in OWT and a new method to calculate RPN number for component level failures in OWT. These modified methods and its derivatives are found to be useful in predicting failures. The results obtained from these methods also support in planning a predictive CBM for OWT (p-CBM-OWT). A new coding system for OWT components is also given.

3.2. Condition Monitoring in WT

Condition Monitoring supports plan CBM by characterising failures and faults in OWT (El Hachemi, 2000; Hameed, et. al., 2009). As CBM offers more financial benefits than TBM and FBM, the usefulness of CM should not be undermined. In Section 3.3 – 3.6 some case studies relating to use of CM in WT are discussed.

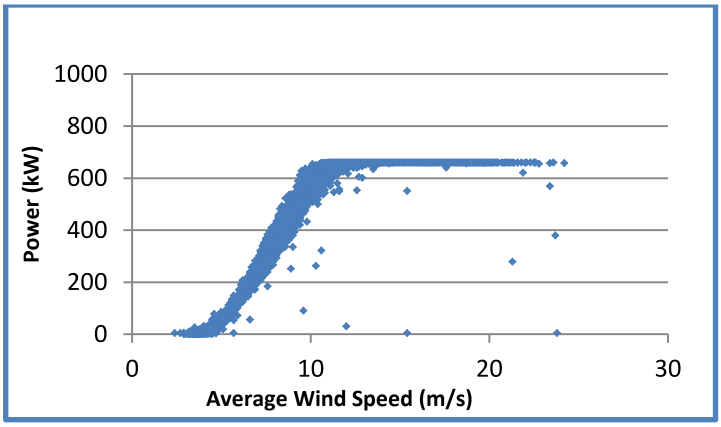
3.2.1 Case Study 1: Use of Wind Turbine SCADA Data

A Supervisory Control and Data Acquisition (SCADA) system collects and transmits the WT controller data to remote location for monitoring and analysis purposes (Thomas, Kumar and Chandna, 2004). Such data can be analysed to detect failures in OWT assemblies/components and support plan predictive CBM.

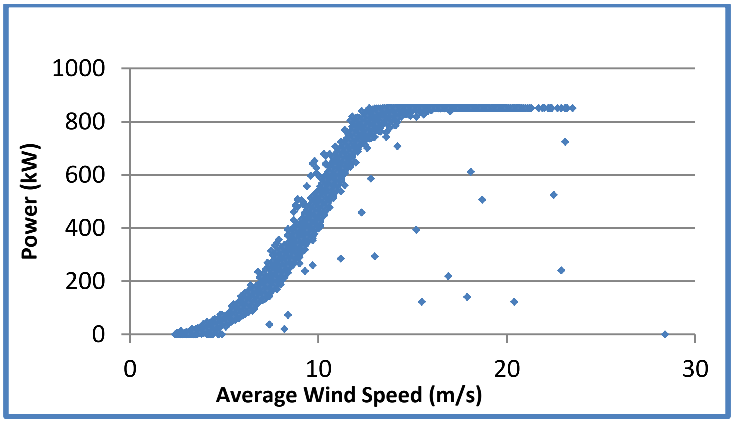
The case study discussed here uses SCADA data obtained from Burradale Wind Farm located in the Lerwick area of Shetland Island, UK. The average wind speed in Lerwick area is very high throughout the year. Burradale Wind Farm generates 3.68MW and meets 18% of Shetland's power demand. It saves 6,200 tonnes of greenhouse gases per year by using wind in electricity generation[V]. There are 3 V47 Vestas model WT that individually generate 660kW. It also has 2 V52 Vestas model WT that individually generates 850kW. The SCADA systems of these WT transmit 60 parameters at 10 min intervals. Some observations made from studying SCADA data were:

1. ~15% of the SCADA data was lost due to various reasons like transmission error, due to noise or due to sensor error.
2. plot of wind speed and power generated by V47 and V52 gave plots as shown in Figure 3.1 (a) & (b) respectively. These represent typical WT power curves.
3. some points on the power curves shown in Figure 3.1 (a) and (b) were found to deviate from the standard curve. These were found to be due to reasons like temporary issue with the motion of Yaw System / Pitch System or both.
4. the study also revealed that when blades of V47 and V52 WT were misaligned by more than $\pm$ 0.1^0 - 0.7^0 to incoming wind, WT power reduced considerably. Likewise a misaligned nacelle reduced WT power by 15% (Figure 3.2). So if WT generates less power in favourable wind, yaw/pitch system need checking.

[V] http://www.burradale.co.uk/about



(a)



(b)

Figure 3.1 Shows a plot between wind speed and power generated by (a) V47 WT (b) V52 WT

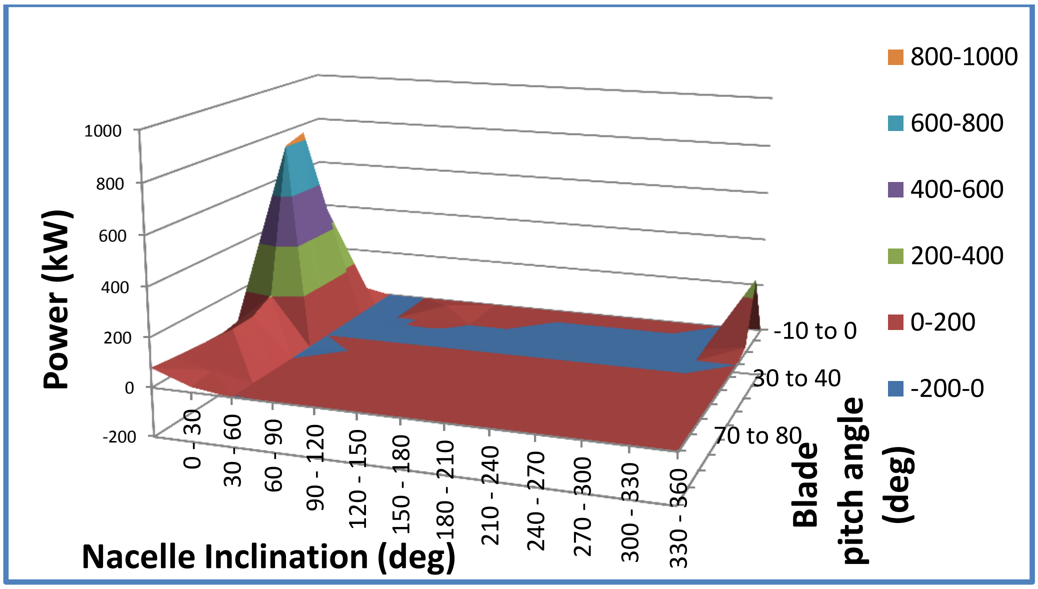


Figure 3.2 Shows the effect of nacelle and blade inclination (with incoming wind direction) on power generation capability of V52 WT

5. Wind Turbulence Intensity is defined as the ratio of standard deviation to the average value of wind speed during a time interval. A plot of shaft bearing temperature was plotted against wind turbulence intensity (Figure 3.3). This plot shows that as wind turbulence increases, the shaft bearing temperature decreases. This is expected as when wind turbulence increases, power generation capability of wind turbine reduces. So if the temperature sensor on the shaft bearing temperature was to give high/low values in cases of high/low wind turbulence intensity respectively, this will indicate failure of the sensor.

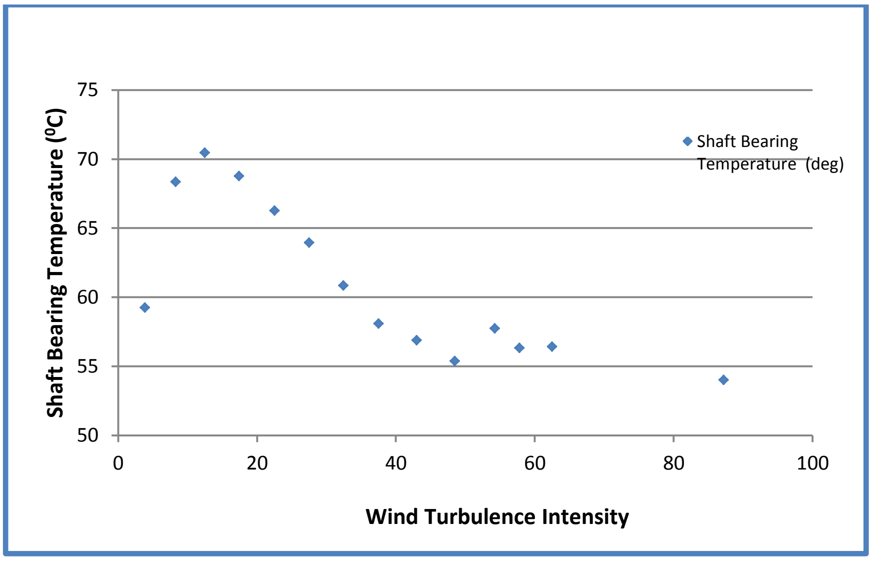


Figure 3.3 Shows the effect of wind turbulence intensity on Shaft Bearing Temperature

If a database is compiled of such failure indicators using WT SCADA data, these can be used to identify failure in WT, their potential root causes and pinpoint failing WT component. These components can then be listed for maintenance.

3.2.2 Case Study 2: Vibration Analysis

Vibration Analysis is a technique in which vibrations in a machine are analysed to identify signature frequencies that correspond to component level failures in the machine (Meirovitch, 1975). This method is widely used to detect failure in rotating parts of machines like in a WT gearbox (Lebold, McClintic, Campbell and Byington, 2000). The diagram of a 3 stage planetary gearbox is given in Figure 3.4. This gearbox is generally connected in between generator and rotor in a WT (Figure 2.1). As a result the two sides of the gearbox are also known as the generator side and the rotor sides of the gearbox (Figure 3.4).

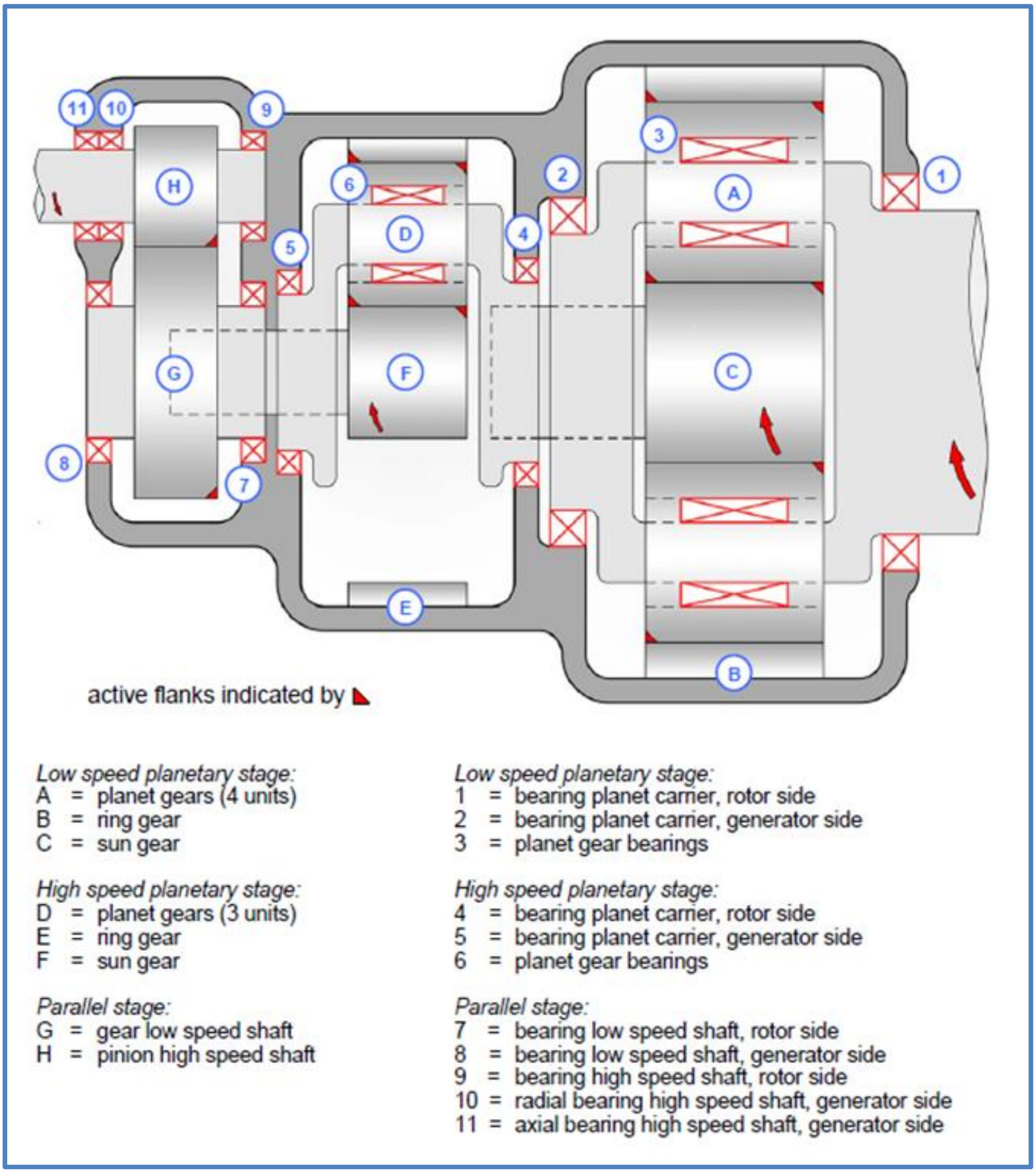


Figure 3.4 Schematic diagram of a Planetary Gearbox of WT

(Source & Permission: Stork Technical Services)

An example of the typical frequency spectrum obtained from vibration monitoring of WT gearbox is shown in Figure 3.5. In Figure 3.5 a plot of vibration (measured in terms of velocity in mm/sec) against frequency has been shown. The spectrum shows spikes at different frequencies where each of these frequencies individually corresponds to different components inside the gearbox. For example the frequencies corresponding to rotational and gear mesh frequencies for high speed shaft, low speed shaft and high speed shaft have been indicated in Figure 3.5. The frequencies indicated in Figure 3.5 arise during normal operation of the gearbox and so such a figure can be taken to be standard for comparison purposes.

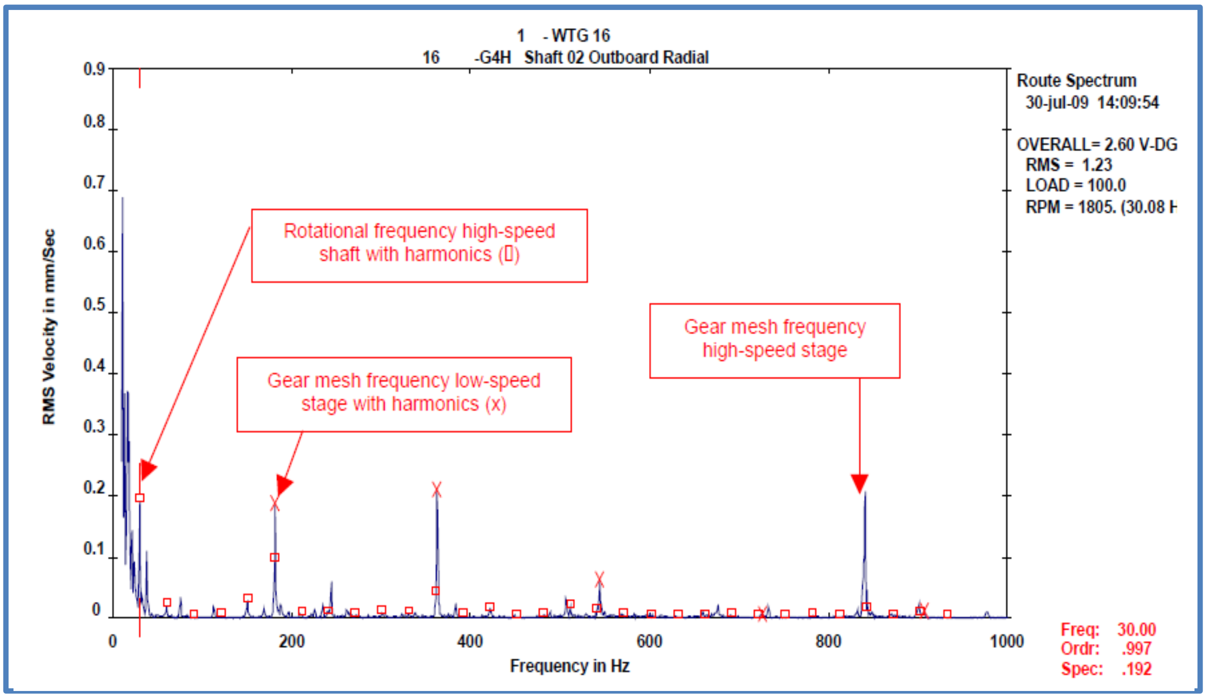
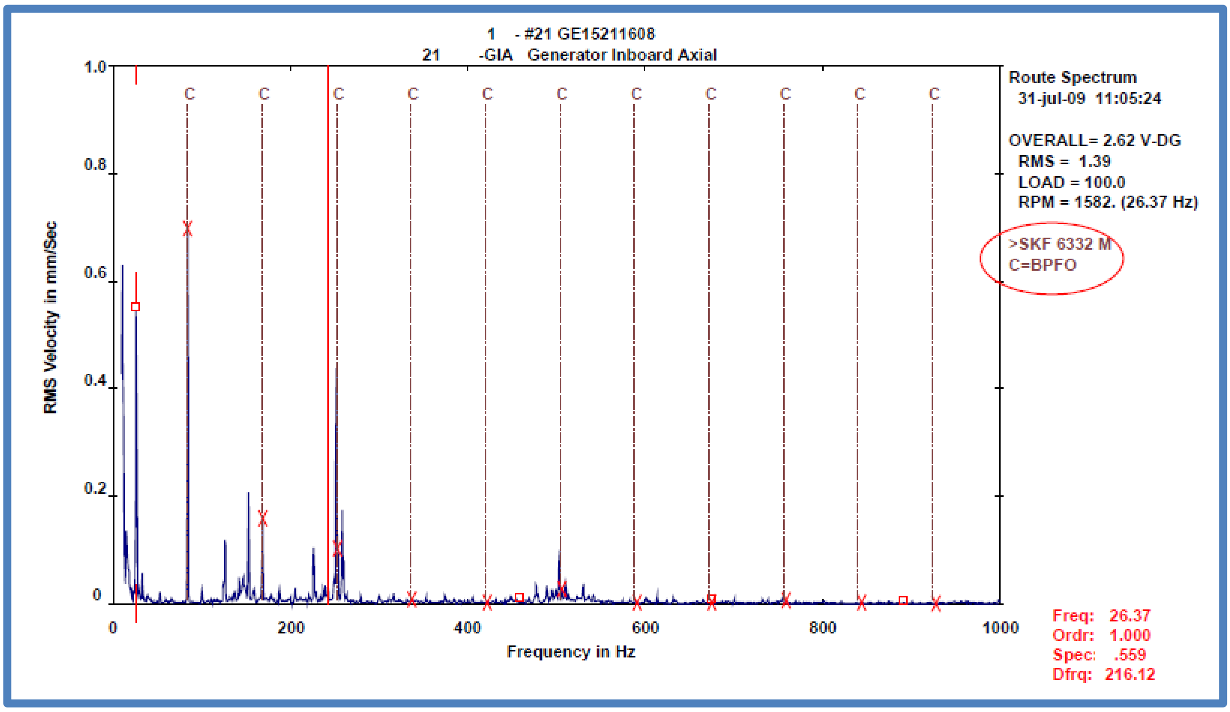


Figure 3.5 Shows the frequency spectrum at intermediate shaft measured in the vertical direction on the rotor side

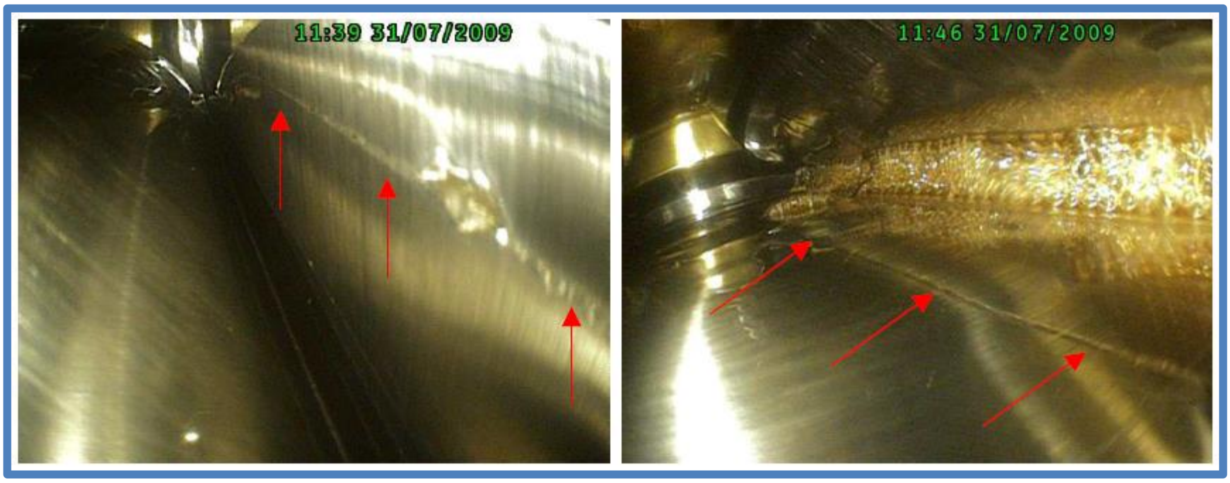
(Source: Stork Technical Services, UK)

By comparing the normal spectrum of a gearbox with other observed spectrums, issues in the gearbox components can be determined and faulty parts identified. As an example in Figure 3.6 (a), a sudden spike at 84 Hz is observed in the frequency spectrum. However this frequency matches with the fault frequency of

SKF 6332 M radial bearing that is used on intermediate shaft at the generator side of a gearbox. This is shown in Figure 3.6 (a). So if this frequency was to occur in the frequency spectrum, a failure in the radial bearing of intermediate shaft can be predicted. As a confirmation, some pictures of the radial bearing are shown in Figure 3.6 (b) that shows surface deformation that gives rise to failure.



(a)



(b)

Figure 3.6 (a) Shows the frequency spectrum depicting failure of the radial bearing on intermediate shaft of gearbox on the generator side (b) visual pictures of the bearing showing surface fault (Source: Stork Technical Services, UK)

As another example, in Figure 3.7 (a) is shown the result of vibration analysis at the low speed shaft of the gearbox. A spike can be seen to develop at 84 Hz (orange circle). When comparing this to Figure 3.6 (a), it indicates that a failure is developing in the radial bearing of intermediate shaft on the generator side of gearbox. Some pictures taken of this radial bearing (Figure 3.7 (b)) suggests surface fault similar to the one observed in Figure 3.6 (b). So if a spike is seen to develop at 84 Hz, surface failure on bearing can be said to be developing. These results indicate that vibration analysis can be used to establish failures in WT.

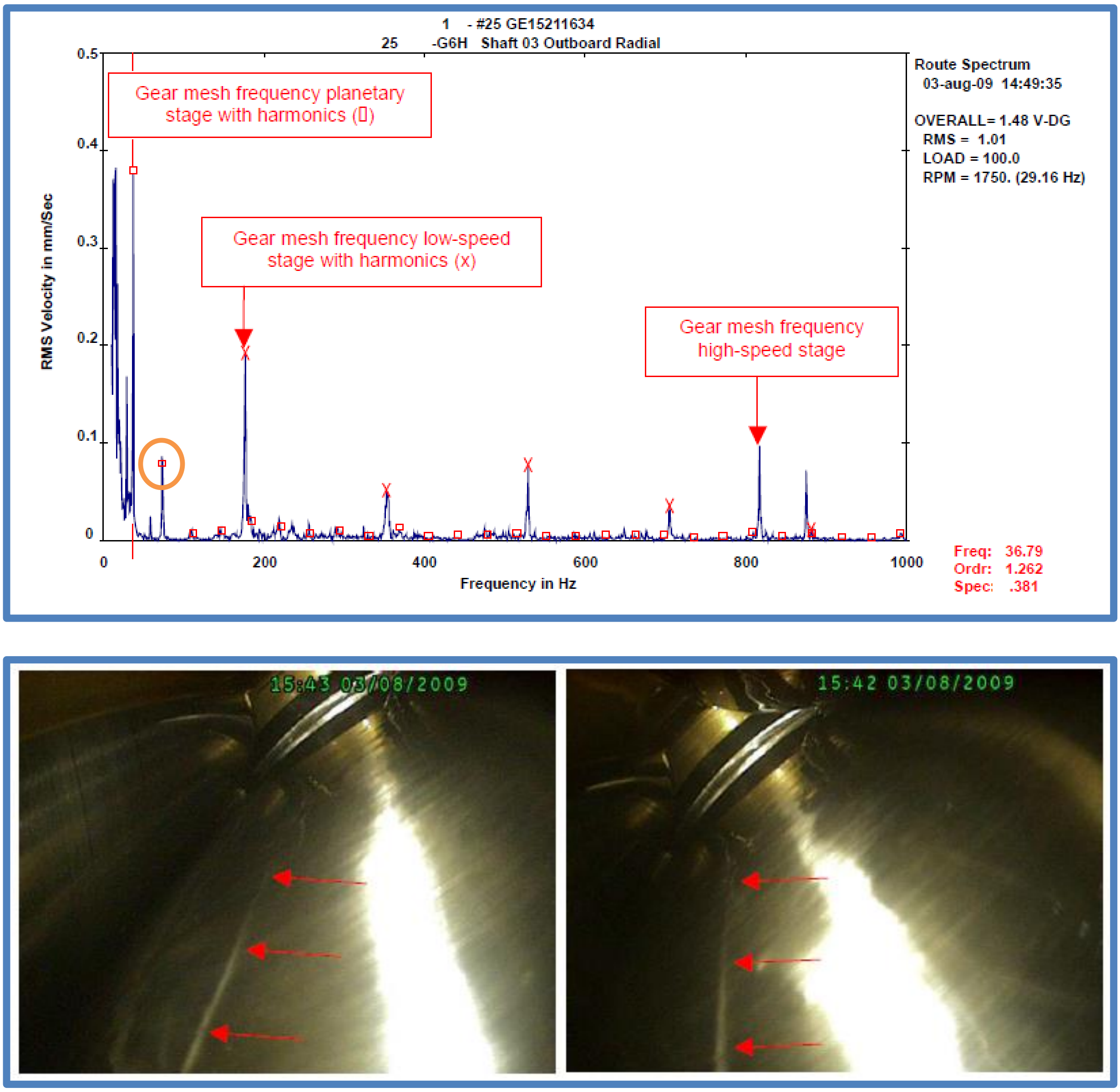


Figure 3.7 (a) Shows the frequency spectrum depicting initiation of failure of radial bearing on intermediate shaft of gearbox on the generator side (b) visual pictures of the bearing showing development of surface fault (Source: Stork Technical Services, UK)

3.2.3 Case Study 3: Lubricating Oil Analysis

Lubrication is a method in which hydrocarbons of suitable viscosity are introduced between moving parts of a machine to reduce wear, tear and rise of temperature due to friction. Lubrication is done using lubricating oil (a fluid) or lubricating grease (a semi-solid). These reduce erosion, corrosion, wash away contaminants (Stepina and Vesely, 1992), produce cooling effect and seal the machine against external agents. However lubricating oil is also useful to analyse the health of a machine by measuring changes in the viscosity of lubricating oil and amount of suspended contaminants in the lubricating oil. Oil Analysis is a simple and economical method that does not need special skills. It can be performed when a machine is operating (online technique) or on standby (offline technique). An analysis of the amount and chemical composition of suspended particles in the lubricating oil gives an indication of the quality of the residual oil, and hence its remaining lifetime, and the level of erosion in the machine, and hence the level of erosion in the components of the machine.

Lubricating oils contain native hydrocarbon elements, called “BASE”, and added supplement compounds, called “ADDITIVE”. The “ADDITIVE” adds special properties to the native hydrocarbon elements to improve performance like anti-oxidation, detergent action, friction jabber, wear resistance and heat dissipation (Stepina and Vesely, 1992). So as long as specialist “ADDITIVE” is present in the native oil, the operational life of native oil and the machine are enhanced.

A study was done to identify if lubricating oil analysis can act as condition monitoring technique to determine the health of WT gearboxes. In this study, lubricating oil analysis reports of over 400 operational WT gearboxes were studied. These WT are located in different countries across Europe and are of different makes and models. However out of these reports only 49 lubricating oil analysis reports were considered in this study. This was since the age of other WT were not known and some reports did not follow similar reporting standards. Some other reports were of individual WT and as a common characteristic of that site could not be established, these reports were not analysed. The schematic diagram of a 3-Stage Planetary gearbox installed in WT was shown in Figure 3.4 while groups have been made of WT gearboxes which operated in same wind farm and had similar age group. This grouping has been shown in Table 3.1.

Groups	Age (years)	WT IDs	Groups	Age (years)	WT IDs
Group 1	2	WT1 - WT17	Group 4	5	WT36–WT39
Group 2	3	WT18 – WT23	Group 5	6	WT40–WT44
Group 3A	4	WT24 – WT26	Group 6	8	WT45–WT49
Group 3B	4	WT27 – WT35	——	——	——

Table 3.1 Lists groups of WT and the number of WT in each group

However it is possible to identify the origin of suspended parts in lubricating oil by matching the chemical composition of suspended parts in lubricating oil with the chemical composition of gearbox components and, the "ADDITIVE" and "BASE" elements in the lubricating oil. This has been shown in Table 3.2. For example if high content of aluminium is found in lubricating oil analysis, this will indicate wear of bushing and thrust washers of the gearbox. Likewise if high concentration of sodium is found in the lubricating oil, this will indicate that the corrosion inhibitor of "ADDITIVE" was being used up in the lubricating oil. When a suspended particle has origin in both the gearbox components and "ADDITIVE" like presence of magnesium, a study of other suspended particles in lubricating oil can provide information about the actual source of element. This indicates that if lubricating oil is analysed on a periodic basis, the concentration level of suspended particles in the lubricating oil can establish failures, identify the root cause of failures and hence can support plan CBM.

Wear Elements from parts of the Gearbox	
Silicon	Dirt Contaminants, Seal, Oil, Coolant, Grease
Iron	Gears, Shaft, Bearings, Housing, gears, bearings, shaft, housing
Copper & Alloys	Bearings, Bushings, Retainers, Thrust Washers and Plates, Cooler Tube
Aluminium Alloys	Bushings, Thrust Washers
Chromium Alloy and Plating	Bearings, Shaft, Seals, Roller Bearings
Lead and Tin Overlay/Flashing	Bearing, Bushings, Grease Contamination
Nickel Alloy (with Iron)	Gears, Shafts, Bearings
Silver Plating	Bearings, Bushings, Oil Coolers, Solder, Seals
Molybdenum Alloy and Plating	Bearing
Magnesium Alloy	Cases and Housing
Titanium Alloy (Lead/Tin)	Journal Bearing Overlays
Zinc Alloy	Brass Fittings, Galvanized Surfaces
Tin	Bearing cage metal, lube additive
Wear Elements from parts of the ADDITIVES	
Molybdenum	Extreme Pressure Additive, Corrosion Inhibitor
Magnesium	Detergent, Dispersant, Alkalinity Increaser, Airborne Contaminant
Sodium	Corrosion Inhibitor in Oils, Salt Water, Air Born, Coolants
Boron	Detergent, Dispersant, Antioxidant in Oils, Coolant inhibitor, Grease
Barium	Corrosion and Rust Inhibitor, Detergent, Anti-Smoke Additive in Fuels
Phosphorus	Anti-wear, Corrosion Inhibitor in coolants, Excessive Pressure Additive
Potassium Compounds	Corrosion Inhibitor, Trace element in Fuels, Mineral Salt in Sea Water
Calcium	Detergent Dispersant, Alkalinity Increaser, Airborne Contaminant, Water
Zinc	Anti-Wear, antioxidant, Corrosion Inhibitor
Lithium	Coolant inhibitor, airborne contaminant, lithium complex grease
Antimony	Anti-wear, antioxidant

Table 3.2 Shows sources of suspended particles found in the lubricating oil of WT Gearbox (Source: Lube Filtration Manual,)

An analysis of lubricating oil inspection reports of Group 1 WT gearboxes reveals a high concentration of Phosphorous (P) (Figure 3.8). This indicates that in initial years of operation, the anti-wear and excessive pressure "ADDITIVE" in the lubricating oil was being used to protect the native hydrocarbons in lubricating oil and the gearbox components against varying stresses (Table 3.2).

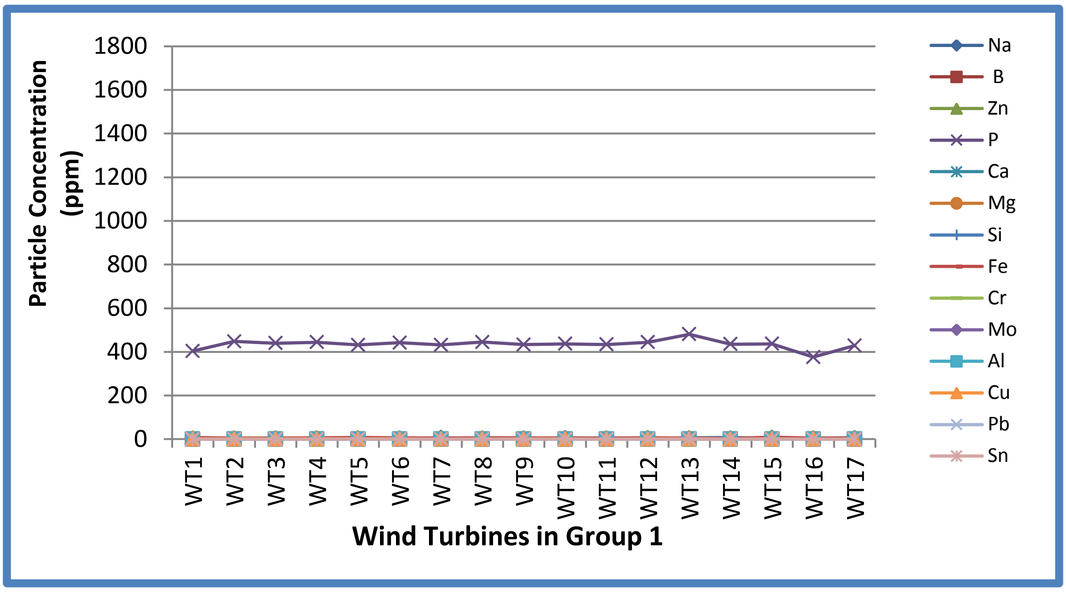


Figure 3.8 Shows variation in particulate concentrations of lubricating oil in the Gearboxes for Group 1 WT

However when number of years in operation increases, like for WT gearboxes in Group 3A & Group 3B, the concentration levels of Magnesium, Zinc, Phosphorous and Molybdenum increased. This shows that "ADDITIVE" and brass fittings of Gearbox were being eroded (Table 3.2). These conditions are shown in Figure 3.9 and Figure 3.10. A low value of particulate concentration in WT27 in Figure 3.10 denotes a possible oil filtration or oil change however no information about this exists.

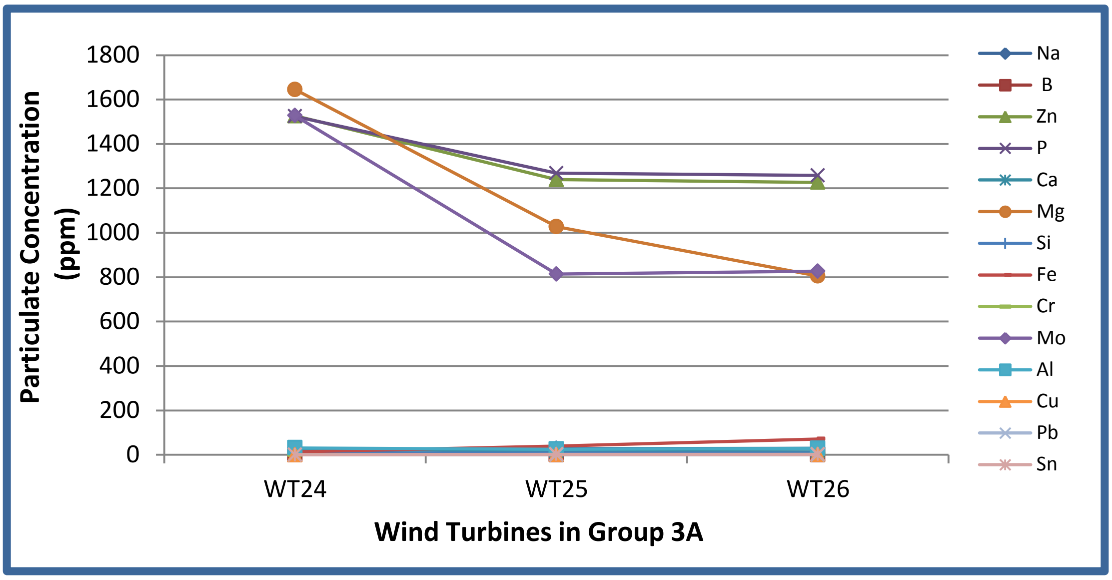


Figure 3.9 Shows variation in particulate concentrations of lubricating oil in the Gearboxes for Group 3A WT

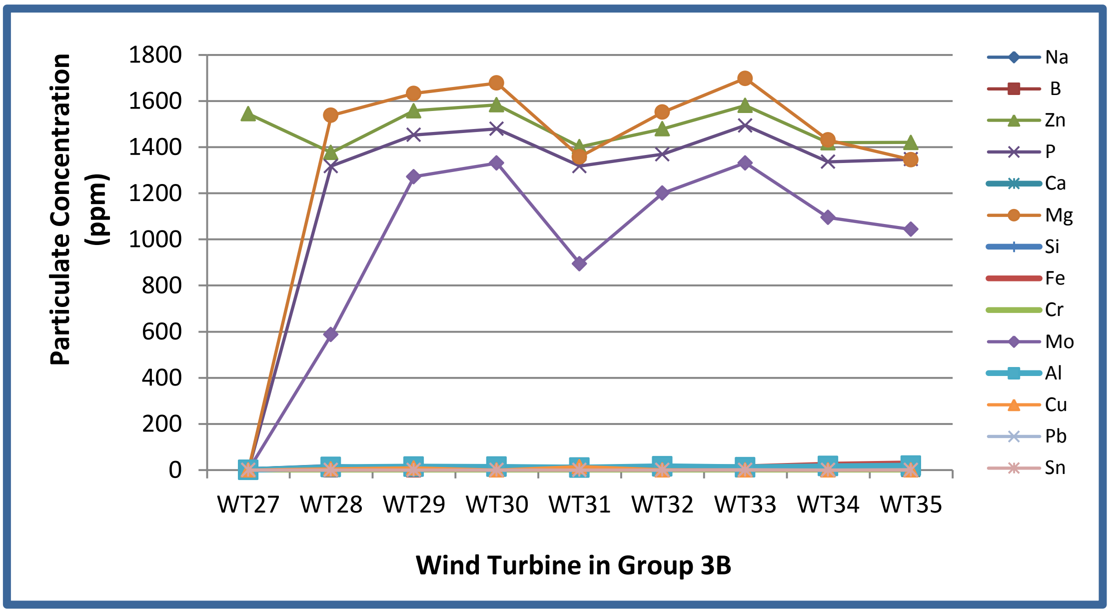


Figure 3.10 Shows variation in particulate concentrations of lubricating oil in the Gearboxes for Group 3B WT

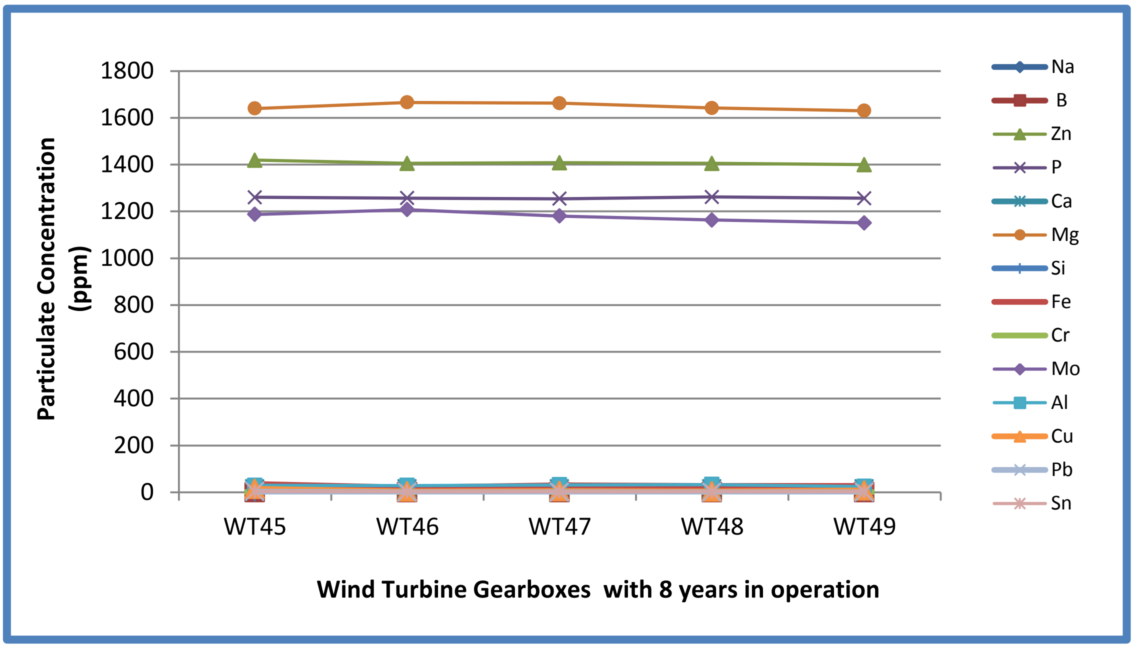


Figure 3.11 Shows variation in particulate concentrations of lubricating oil in the Gearboxes for Group 6 WT

In Figure 3.11, the concentration level of suspended particles in lubricating oil of Group 6 WT gearboxes is plotted, i.e. 8 year old WT gearboxes. In Figure 3.11, a high concentration level of many suspended particles in the lubricating oil shows a possible origin in brass fittings, galvanized surfaces, casing and bearings. This indicates that WT components are being corroded and failures are expected. In Figure 3.12, variation in National Aerospace Standard (NAS) number for various WT groups is shown. It is seen that roughness in the lubricating oil increases (high value of NAS) with years in operation and result in more impure oil.

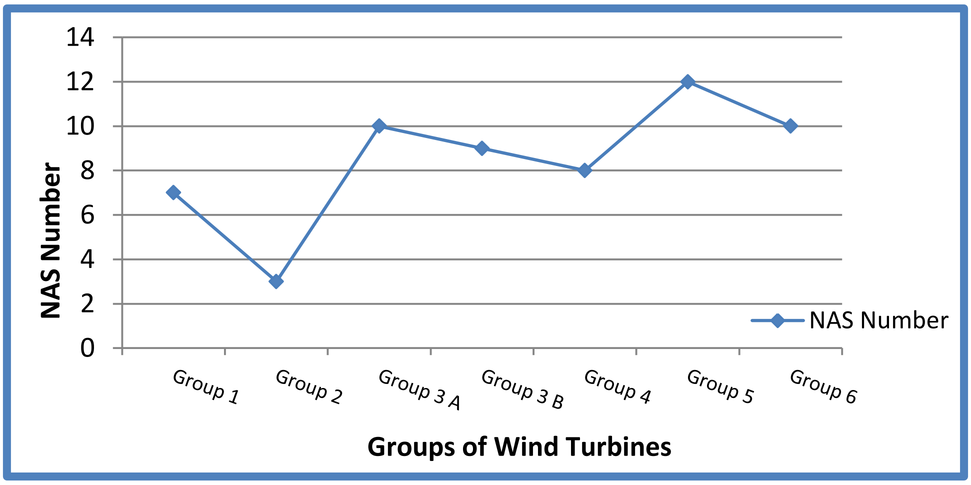


Figure 3.12 Shows a plot of NAS number for the different groups of WT

These observations indicate that “ADDITIVE” in lubricating oil protects Gearbox against wear and tear. If the life of Gearbox and lubricating oil were to be prolonged, there is a need to replenish its “ADDITIVE” on a periodic basis. This would optimise the performance of lubricating oil while protecting the internal surfaces of the gearbox against wear, tear and abrasions. These observations also indicate that by analysing a sample of lubricating oil it is possible to predict component level failures in WT gearbox for which proactive remedial actions can be planned. However it is equally important that correct amount of lubricating oil is maintained in gearbox as leakage and consumption over a period of time reduces its volume that can result in failures like seizure, wear and pitting.

3.2.4 Case Study 4: Visual Analysis

Visual Analysis is yet another popular technique where failures are detected by seeing, feeling by hand or by smelling (Drury, 2002). Where physical access is limited or costly, remote controlled cameras with probes are used to take picture of machine components. These pictures are analysed to identify failures and their potential root cause. An illustration of visual analysis use in WT gearbox is given in Figure 3.13. In Figure 3.13 the internal components of WT gearbox are pictured without disassembling the gearbox. These pictures show the condition of internal components in a gearbox. This includes meshing interferences, pitting, faulty air breathers and low level of oil. These pictures (/visual analysis) give evidence of impending failure and their careful analysis can provide information about their root cause. As these pictures enable determination of the status of gearbox components without dissembling the gearbox, visual analysis can be performed in short time. This has financial benefits over other methods that take prolonged time for condition monitoring.

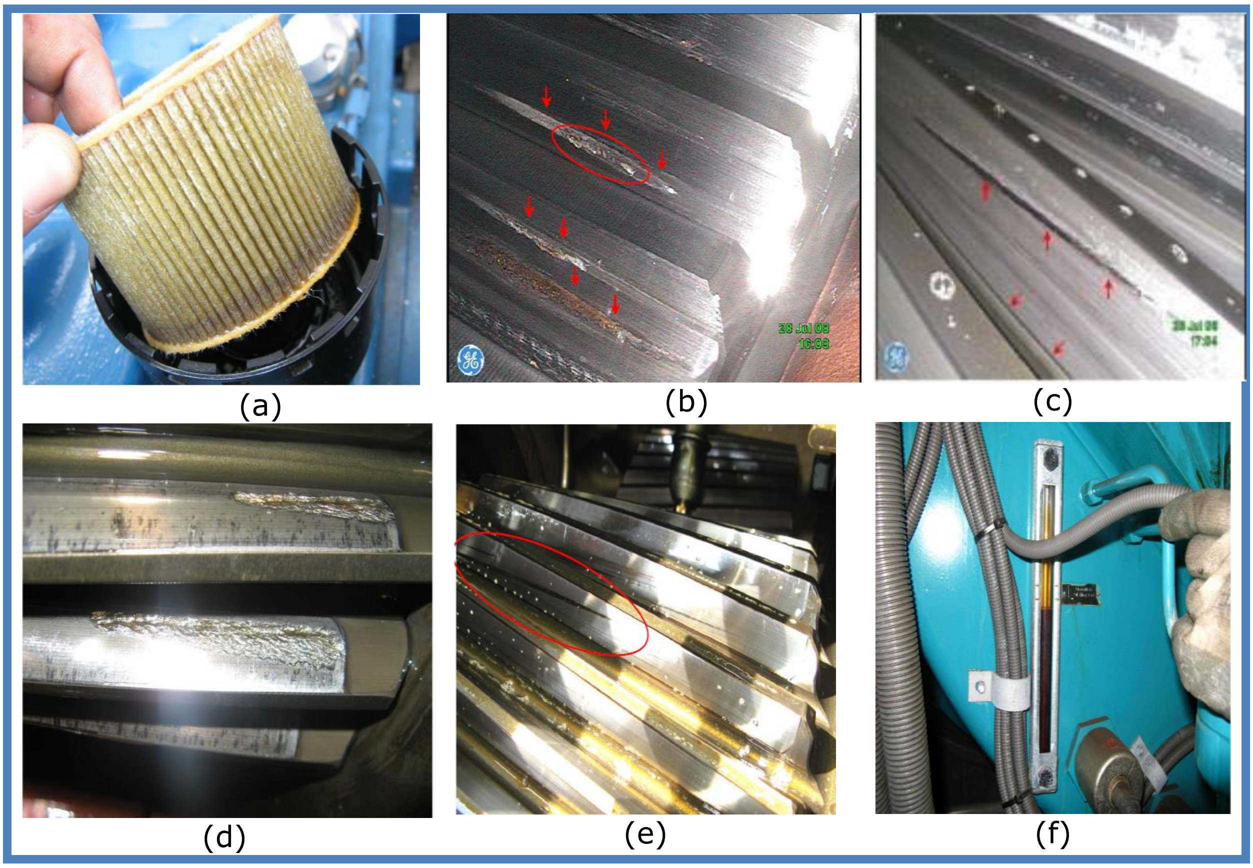


Figure 3.13 Shows images obtained from visual inspection of wind turbine gearbox

(a) Air Breather Filter (oily), (b) ring Gear Intermediate Shaft (Pitting), (c) Planet Gear Low Speed Side (Meshing Interference), (d) Pinion Intermediate Speed Shaft (heavy corrosion), (e) Pinion High Speed Shaft (Pitting), (f) Oil Level Indicator (low oil level), (Pictures & Permission: Stork Technical Services, Aberdeen)

3.3. An Overview of generic failures in OWT-COCA

In Section 2.4, Gearbox, Generator and Electrical Systems were identified to be the COCA for OWT. However in order to plan CBM for OWT-COCA it is required that their failures are identified and analysed. In Table 3.3 and Table 3.4 generic failures in OWT-COCA components (identified by EU FP7 ReliaWind Consortium) have been listed. It can be seen from Table 3.3 and Table 3.4 that failures result from: aging, overuse, human factors, failures in any supporting systems (like lubrication system), change in operating condition, extended use in spite of observed failure (like degraded output), and many more avenues. However while mechanical systems showed more wear and tear type failures, electrical systems predominately shows intermittent, shorted and open circuit failures and faults.

Assembly	Subassembly	Component	Generic Failures – Failure Modes
Gearbox / Generator	Gearbox Bearing	Carrier/Planet/ Shaft	Worn, Binding, Sticking, Seized, Jammed, Excessive Play, Dry/No Lubricant, Misaligned, Fitting Issue, Pitted, Aged, Scored, Corroded, Brinelling, Vibrations, Clogging, Fatigued, Induced
	Generator Bearing	Shaft/Rear	
Gearbox/ Generator	Cooling/Lubrication System	Hose	Broken, Worn Out, Cracked/Fractured, Leaking, Induced
Gearbox/ Generator	Cooling/Lubrication System	Pump	Leaking, No Operation, Shorted, Seal/Gasket Failure, Induced, Misalignment, Degraded Operation, Bearing Failure, Mechanical Failure, High Current, Drift, Cooling Failure, Intermittent Operation, Lubrication problem, Burned, Fatigued, Corroded, Cavitation, Failure to Start
Gearbox	Gears	Shaft	Seized, Cracked, Warped, Rusted, Induced, Alignment Issue
Gearbox	Gears	Bushing	Loose, Corroded, Misfire, Aged/Deteriorated, Fracture, Loose, Scarred, Induced
Gearbox	Housing	Case	Binding, Excessive Use, Broken, Cracked, Misaligned, Skipping, Induced, Leaking Lubricating Oil
Gearbox	Housing	Mounting	Broken, Excessive Play, Loose, Induced
Gearbox	Lubrication System	Filter	Leaking, Improper Output, Clogged, Degraded operation, Cracked, Broken, Out of Specification, Burst, Warped, media Migration, Channelling
Gearbox	Lubrication System	Seal	Leaking, Cut, Punctured, Aged, Worn, Loose, Induced, Gasket Failure, Cracked
Gearbox / Generator/ Communication System	Sensors	-	Degraded Output, Opened, Shorted, No Operation, Zero or Maximum Output, Drifting Output, Closed, Internal Failures, Induced, No Signal Output, Mechanical Failure
		Temperature	Changed Resistance Value, Zero or Maximum Value, Degraded Output, No Operation, Function without Signal, Induced
Generator	Cooling System	Fan	Noisy, Intermittent Operation, Displacement, No Operation, Out of Adjustment, Sticking, Mechanical Failure
AES	Electrical Services		
Generator	Cooling System	Filter	Leaking, Improper Output, Clogged, Degraded operation, Cracked, Broken, Out of Specification, Burst, Warped, media Migration, Channelling
Generator	Rotor	Resistance Controller	Opened, Drifting, Shorted, Moisture Intrusion, Mechanical Failure, Non-Uniform Resistance
Generator	Rotor	Slip Ring	Opened
Generator	Sensor	Encoder	No Movement, Resistor Failure, Optical Assembly Failure, Lamp Failure, Incorrect Antenna Rotation, Cracked, Casing Rotates, Induced
Generator	Sensor	Wattmeter	Degraded Output, No Output, Induced
Generator	Structural & Mechanical	Housing	Binding, Excessive Use, Broken, Out of Adjustment, Skipping, Induced
Generator	Structural & Mechanical	Silent Block	Worn Out, Aged, Misfire, Loose, Induced
AES	Electrical Services	Auxiliary Transformer	Degraded Output, Mechanical Damage, No Output, Open Circuit, Induced
AES	Electrical Services	Circuit Breaker	Struck Open, No Movement, Connector Failure, Out of Adjustment, Stuck Closed, Intermittent Operation, Seized, Induced
AES	Electrical Services	Cabinet	Cracked, Out of Adjustment, Broken, Worn, Battery Failure, Binding, Induced
AES	Electrical Services	Grid Protection Relay	Fails to Close, Open Coil, fails to Open, Shorted, Induced
AES	Electrical Services	Light	Lamp Failure, Broken, Loss of Control, Shorted, Cracked, False Operation, Grounded, Induced
AES	Electrical Services	Switch	Drift, Open, Mechanical damage, Intermittent Operation, Shorted, Induced
AES	Electrical Services	Pushbutton	Open, Contaminated, Shorted, Induced
AES	Electrical Services	Relay	Contact Failure, Aluminium Migration, High Contact Resistance, Intermittent Operation, Shorted, Loss of Control, Spurious Opening, Induced
AES	Electrical Services	Space Heater	Opened, Shorted, Protection Failure, Jacket Rupture, Induced
AES	Electrical Services	Surge Arrester	Broken, Punctured, Worn, Induced
AES	Electrical Services	Thermal Protection	Drift, Mechanical Failure, Opened, degraded Operation, No Output, Loss of Control, Shorted, Induced
AES	Electrical Services	UPS	Fails to transfer, No Output, degraded Operation, Induced

Table 3.3 Lists generic failures in OWT- COCA, i.e. Gearbox, Generator and AES

(Source: Maintenance / Service Records, Troubleshooting Guides, RAC 1991 Failure Datasheet)

Assembly	Subassembly	Component	Generic Failures – Failure Modes
Control System	Ancillary Equipment	Breaker	Opens without Command, does not open, degraded operation, cracked, broken, mechanical failure, induced
Control System	Ancillary Equipment	Cabinet Temperature	Change in resistance, Zero or Maximum Output, Degraded Output, No Operation, Functions without signal, Induced
Control System	Ancillary Equipment	Cable	Broken, Induced
Control System	Ancillary Equipment	Contactor	Broken, Sticking
Communication System	Communication System	Digital I/O	Erroneous Digital Signal
Communication System	Communication System	Field Bus Master	Broken, Aged
Communication System	Communication System	Frequency Unit	No Operation, Shift in Frequency
Communication System	Communication System	Condition Cables	Opened
Communication System	Communication System	Data Logger	Intermittent Operation, Induced
Communication System	Controller Hardware	Controller Power Supply	Incorrect Voltage, No Output, Distribution System, Connector Failure, Generator System Malfunction, Connector Failure, Generation System Malfunction, OpAmp & Diode failures, Transmission System failure
Communication System	Controller Software	Supervisory Control Software	Design Problem, User Error, Documentation Error, Other Induced reasons

Table 3.4 List of generic failures in OWT-COCA, i.e. Gearbox, Generator and AES (Source: Maintenance / Service Records, Troubleshooting Guides, RAC 1991 Failure Datasheet)

An analysis of failures listed in Table 3.3 and Table 3.4 shows that failure in lubricant oil, coolant, lubrication and cooling systems, result in 40% of all generic failures in OWT-COCA. The failures in mechanical systems like binding, sticking, worn, aged, cracked and fractured surfaces account for nearly 20% of all generic type of failures while 18% of all generic failures arise in the electrical and electronic components. Also, nearly 45% of all generic failures in OWT-COCA could be avoided by low cost preventive maintenance and are easily detected by existing inspection methods while 20% of all generic failures are avoidable by timely intervention. As failures in mechanical systems take longer to develop and repair than electrical systems, timely interventions should be planned to prevent mechanical failures from developing into bigger faults. But failure in electrical systems can completely shut down an OWT and so high grade and highly reliable electrical components should only be used. Failsafe systems should be implemented for all low cost but critical operations, like lubrication and coolant systems so that if one fails the standby system can replace faulty system.

3.7. A modified FMECA to analyse failures in OWT

Planning for CBM requires evidence of machine failure which is obtained from condition monitoring, as shown in Section 3.2.1 – 3.2.4. However in order to plan CBM for OWT, ISO 17359 guidelines require that component level failures in OWT are analysed (Section 1.4). Such analysis should identify the root causes of failure, its severity, remedial actions and preventive methods. Some failure analysis methods that achieve such objectives were discussed in Section 2.9. Some other techniques are Preliminary Hazard Analysis, Relative Ranking, What-If Analysis, Checklist Analysis, Fishbone diagram (Duffuaa and Ben, 1995), Pareto Charts and Root Cause Map (Rooney and Heuvel, 2004). However as identified in Section 2.9, FEMCA offers the flexibility of analysing failures using qualitative and quantitative approaches and has a structured framework that is critical for managing failure analysis of >10,000 components of electrical, mechanical, electronic, computing and structural nature in OWT. This is important as failure analysis offers financial advantages and assists in maintenance (Stamatis, 2003) and so choice of a failure analysis technique that is complex to implement will be counterproductive in practical use.

However the framework of FMECA in its native format has many limits and need to be moderated to achieve objectives of OWT maintenance. Some of the limitations of FMECA include

(i) <u>Subjectivity</u>: FMECA offers flexibility of using different standards that in turn provides different values to quantities and hence give rise to ambiguities,

(ii) <u>Prognostic Approach</u>: FMECA only talks about static failures and no comment is made on the state of failure with changing time,

(iii) <u>Multiple Agents</u>: FMECA cannot identify the exact root cause of failure if multiple agents acted simultaneously to generate a failure/fault,

(iv) Internal/External Agents: FMECA does not provide the facility to analyse effect of an existing failure on other components, nor does it identify the effect of external factors like wind turbulence, temperature, lubricating oil.

(v) Time Varying Parameters: FMECA does not offer the facility to analyse effect of time on failures, wind turbine operation, component aging.

(vi) Repair Time: FMECA does not consider repair time while analysing failures

(vii) Effect of No or Deferred Maintenance: FMECA does not analyse the effect of delaying maintenance.

A modified framework of FMECA, FMECA - plus ($FMECA^+$), is suggested in this work that overcomes above limitations. Whereas the traditional FMECA contained fields to:

i. Identify all components in OWT
ii. Identify failures in OWT components
iii. Identify the root causes of failures
iv. Identify the effect and consequences of the failures

the $FMECA^+$ framework additionally provides provision to:

v. Identify effect of external agents – like wind, wave, temperature
vi. Identify effect of deferred maintenance
vii. Identify resolution/compensatory provisions for failure
viii. Rank failures based on different Qualitative / Quantitative avenues
ix. Identify cost category for servicing of failures
x. Identify effect of human/technical/management errors
xi. Identify impact of a failure on other components and/or other failures

So henceforth the native format of FMECA will be termed as traditional-FMECA (t-FMECA) while the proposed framework will be termed FMECA-plus ($FMECA^+$).

The framework for FMECA$^+$, which is in line with t-FMECA but contains additional fields as mentioned in the list on last page, is shown in Table 3.5.

Group	Fields	Group	Fields	Group	Fields
Define System	Subsystem	Futuristic Condition of Failure	Time	Qualitative Analysis	Level A – Frequent
	Assembly		Effect of Failure Causes		Level B – Reasonably Probable
	Sub-Assembly		Effect of Subassembly		Level C – Occasional
	Component		Effect of Assembly		Level D – Remote
Define Failure	Description		Effect of Subsystem		Level E – Unlikely
	Mode	Failure Effect Analysis	Effect on Component	RPN Number	Severity
	Nature		Effect on Subassembly		Occurrence
	Type		Effect on Assembly		Detection
Root Cause	Cause 1		Effect on Wind Turbine		RPN Number
	Cause 2	Resolve Failure	Detection Method	Costs	Spares
	Cause 3		Isolation Method		Services
	Primary Cause		Compensation Method		Transport
Effect of Agents	Wind		Rectification Method		Miscellaneous
	Humidity		MTTR	Prioritising Failures	According to Effect
	Water Waves	Quantitative Analysis	Failure Effect Probability		According to Future Conditions
	Temperature		Failure Mode Ratio		According to RPN Value
Effect of Prolonging Upkeep	Effect on Failure		Part Failure Rate		According to Maintenance Cost
	System Performance		Operating Time		According to MTTR
	Consequences Rating		Criticality Number		Prevailing Future Condition
	Downtime		Item Criticality Number	Risk	Prone to Human Error?
	MTTR		System Criticality Number		Prone to Specification Conflict?
	Maintenance Cost		Wind Farm Criticality Number		Prone to management Error?

Table 3.5 A recommended list of fields for FMECA$^+$ of OWT (Darkened areas represent new additional fields)

In FMECA$^+$ the OWT is divided into its subsystem, assembly, sub-assembly and components. The failures at all these levels are determined. Later the root causes of all such failures are identified. The effect of external agents (wind, humidity and temperature) on WT component failure is determined. The effect of prolonging maintenance and its effect on failures is also determined. The effect of prolonging maintenance on failure and its effect on the performance of subsystem, assembly, sub-assembly and components are also determined. The failures identified at the subsystem, assembly, sub-assembly and component levels are ranked using various Qualitative and Quantitative methods like RPN number, costs and risk. A database of over 800 generic failure and root cause combinations has been compiled in this work for components in OWT-COCA. These failures are analysed using the FMECA$^+$ framework shown in Table 3.5.

The framework given in Table 3.6 offers several advantages. These include the ability to uniquely store failures of each component, ability to identify common failures and root causes of failure, ability to study the effect of external agents on component failure, ability to identify the future status of a failure if maintenance gets delayed, ability to study the impact of maintenance deferment on failing wind turbine components and its repercussions on wind turbine performance, identify nature of maintenance needed to rectify different types of failures, ability to rank failures on many criterion like severity, occurrence, detection, risk priority number, maintenance cost, and ability to identify failures that are susceptible to human fallacies during maintenance.

A preliminary analysis of failures in OWT-COCA using FMECA$^+$ framework results in several outcomes. For example it becomes possible to identify components that get influenced by external agents and show failure. This is shown in Table 3.6.

Agent	Failure Mode	Component Effected
Water	Corrosion	Bearing, Pump, Transformer, Cabinet,
Water, Wind	Rust	Shaft, Bushing, Cabinet, surfaces, gearbox mounting
Water, Wind	Cavitation	Pump, Bearing, Rotor, Coupler, Gearbox casing, housing
Wind	Material Fatigue	Pump, rotor, main shaft, coupler, generator shaft, gears
Humidity	Moisture Intrusion	Rotor Resistance Controller, Sensors, Lubricating Oil, coolant
Dirt, Silica, Humidity	Contamination	Switches, Lubricating Oil, Coolant, Grease, Seal, Breathers

Table 3.6 Shows components affected by external agents and their failure modes

Another example of using FMECA$^+$ is shown in Table 3.7 where the effect of delaying maintenance on components and failure type are listed. The effect of delaying maintenance is studied under Constant Degradation (No effect), increasing degradation (failure becomes prominent), rapid degradation (failure becomes very prominent in time) and complete failure (failure becomes fault). For example if a transmission shaft was to become slightly out of adjustment, chances of its failure becoming prominent with time will increase and hence it will be under increasing degradation category. However if the same transmission shaft was to become out of alignment by significant margin, the effect of delayed maintenance will place such failure under the Rapid Degradation or Complete

Failure category based on the level of misalignment. So depending on the type of a failure and its severity level, the impact on failure for delayed maintenance is studied. This is useful to identify failures requiring prompt maintenance.

Effect on Failure	Components Effected	Failure Type
Complete Failure	Sensor, Controller Power Supply, Internal Communication System, Bearing, Pump, Gears, Oil Filter, Lights, Faulty Switches	Conductor/Connector Failures, Failing or Intermittent Sensors, Seizure of bearing, mechanical damage of filter, defective light, short/open circuit components
Rapid Degradation	Bearing, Housing, thermal protection system, software problem, exciter	Material fatigue, aged components, unserviceable parts, output errors from software, aged bushings, etc.
Increasing Degradation	Various bearings/shaft and housing system, seal, couplers, rotor lock, transmission shaft, axial bearing, Fan, Switch, Surge Protection	Out of adjustment, intermittent outputs, Warped, worn, broken/fractured, jammed switch, intermittent, noisy, misaligned, cracked, lack of lubricant, vibration
Constant Degradation	Sensor, CPU, circuit breaker, UPS, common mode filter, coupler, connector plate, radial bearing, rotor lock	Worn, scored, corroded, leaking, induced, Erratic output, rust, corrosion, cavitation, constant degraded output

Table 3.7 Shows components affected by maintenance deferment and their failure type

As another example, in Table 3.8 the effect of maintenance deferment on system performance is shown. For example, failures like binding and seizure would have a severe effect on the performance of bearing, shaft and rotor lock where they will operate at top stress levels. Similarly loss of lubricant or loose connections would have high effect on performance of gearbox shaft, coupler and speed sensor and cause severe failures.

Effect on System Performance	Failure Type	Components Effected
Severe Effect	Binding, Seizure, Broken, Cracked, Fractured, Jammed	Bearing, Temperature Sensor, High Speed Shaft, Rotor Lock, Compression Coupling, Connector Plate, Main Bearing Seal, Rotor Lock, Mechanical Brake, Generator Core Temperature Sensor
High Effect	Loss of Lubrication, Skips, cable shorted, no output, Loose connection, slippage	Lubrication / Cooling System, Gearbox Shaft, Loose Coupler, High Speed Sensor, Rotor Lock, UPS, Supervisory Control Software, Brake
Moderate Effect	Vibration, Alignment Errors, No Transmission, Burned, Fatigue, Stripped, Displaced, Erratic Output	Gearbox Case, Gearbox Mounting, Lubricating Oil Hose, Cooling System Pump, Generator Cooling Fan, Core Temperature Sensor, Radial Bearing, High Speed Sensor
Low Effect	Aged components, Scored, Corroded, Worn Out, Cavitation, Rust/Rusted, Clogged, Out of Tolerance	Damage to filter, hose, coupling shaft, Fan, cabinet, switch, surge arrester, thermal protection, Cabinet temperature sensor,

Table 3.8 Shows the effect of maintenance deferment on WT system performance

Likewise the effect of a failure on nearby components can be studied using the FMECA^{+} framework. This is shown in Table 3.9.

Consequence Rating	Failure Type	Components Effected
Severe	Defective, misalignment, seized, frozen, part missing, loose, binding, worn shaft, keyway seized, improper maintenance, function at improper signal level, opened cables, fuse blown	Carrier Bearing, Planet bearing, encoder, High Speed Shaft Coupling, Rotor Lock, Transmission shaft
Very High	Binding, Sticking, Seized, Jammed	Gearbox Bearing, Gears, Generator housing
High	Excessive Play, Loose, Damaged, Bent, Dented, Warped, broken, fails to start, intermittent operation, Induced, Broken, Improper Output, skipping, Lubrication dried out,	Generator Rear bearing, Generator shaft bearing, Generator Wattmeter Sensor, Generator Encoder, Main Shaft Set Coupling, Electrical Switch, Relay
Moderate	Worn, Corroded, Loose, Bent, Dented, Warped, Induced, Mechanical Failure, Burned Out, Fails to Start, Noisy, Intermittent, Cracked/fractured	Pump, Mounting, Case, Bushing, Sensor, Housing, Radial Bearing, Low Speed Sensor, Position Sensor
Low	Scored, Clogging, Noisy, Short, Open, Drifting, Cooling issue, fatigue, cavitation	Pump, coil, hollow shaft, bushing, hose, filter, seal, primary filter, secondary filter

Table 3.9 Shows the effect of maintenance deferment on the consequences of failure

However not all failures are found using remote inspection and monitoring i.e. by using *Detection Methods*. For example failures like fatigue, unbalanced loading, logical and human errors and programming errors are difficult to detect remotely. In such situations methods like *Isolation* (removing failed component and test using good component), *Compensation* (using an additional component alongside failed component) and *Rectification* (test rectified component in operation) are used (Simani, Fantuzzi and Patton, 2003; Mosterman and Ghidella, 2004; Meyer and Zakrajsek, 1990). But these methods require human intervention and require costly offshore travel. This adds to maintenance cost.

A study was done using the FMECA$^+$ framework (Table 3.5: Resolve Failure) to establish strategies for identification of generic failures in OWT-COCA for given root causes of failures. The results of this study shows that of all generic failures in OWT-COCA, 73% of them could be identified by existing inspection/monitoring techniques (*Detection Methods)*, however 32%, 17% and 45% of all generic failures additionally or alternatively may also require *Isolation*, *Compensation* and *Rectification Methods* for the detection of generic failures in OWT-COCA. This is shown in Figure 3.14. It is inferred that there is a need for better failure detection methods that can remotely detect failures of diverse natures. This will cut offshore based inspection costs and so control OWT maintenance cost.

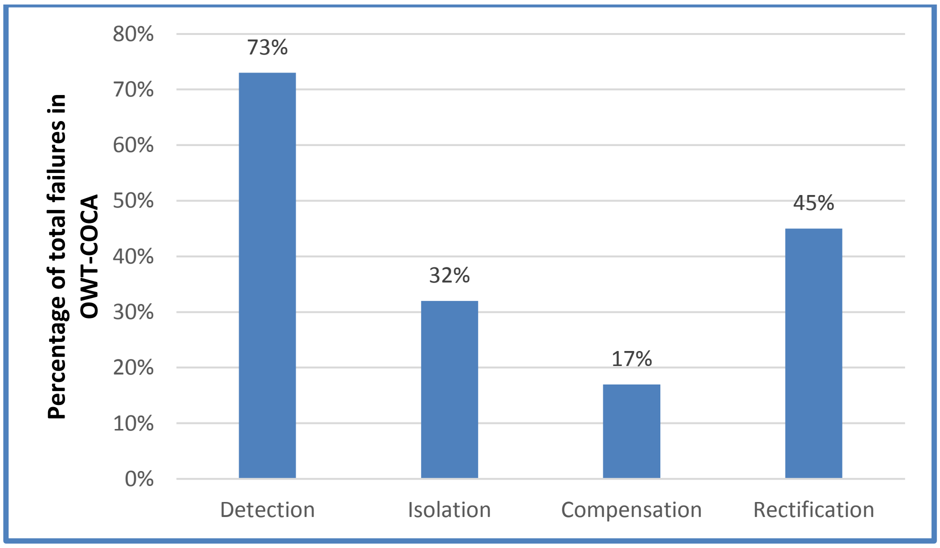


Figure 3.14 Shows comparison of failure identification methods used for OWT-COCA

3.8. Ranking of Failures

In Section 2.9 it was mentioned that Risk Priority Number (RPN) is often used to rank failures in order to prioritise maintenance of critical failures. This helps prevent catastrophic failures and reduce WT downtime. The RPN value is calculated using Equation 2.7. However it was identified that use of RPN in ranking failures suffer from Subjectivity and Inconsistency. For example choice of Severity, Occurrence and Detection (S,O,D) values depend on personal decision and result in Subjectivity in RPN value. For example, if two people choose (4,6,4) and (4,6,5) for (S,O,D) for same failure, the RPN value evaluates to 96 and 120 respectively. A single digit difference in (S,O,D) value alters rank of the failure by 24. For OWT that contains thousands of failures, such altered ranks will create confusion in planning maintenance and possibly lead to maintenance errors. Also, the RPN system uses many standards (Arabian-Hoseynabadi, Oraee and Tavner, 2010; Das, et. al., 2011; Tavner, et. al., 2010) from which value of (S,O,D) are obtained. For example if 2 maintenance planners choose 5 point and 10 point tables to find (S,O,D) values, their RPN values will be incomparable and such results will introduce *Inconsistency* in maintenance plans. As OWT contain thousands of components and thousands of root cause and failure combinations, it is expected that Inconsistency and Subjectivity will be introduced in RPN value calculation. There is a need to develop a less Subjective and Consistent method to calculate RPN value to rank failures.

A new scheme is proposed in this work to calculate RPN value. This scheme calculates RPN value by multiplying the values of Severity, Occurrence and Detection (S,O,D) for a failure however the scheme of finding (S,O,D) values differs as it does not make use of the existing 5,8,10 point tables. Instead the new scheme to find values for (S,O,D) is influenced by a need to:

A1. control ambiguity by limiting choices from which value of (S,O,D) are found. For example in the 10 point system, the probability of choosing a correct value for (S,O,D) is 10% while likelihood of correct RPN value is 0.001.

A2. limit categories of failures which otherwise will make dealing with tens of thousands of failure types in OWT complex and difficult to handle. For example in the 10 point system, there are 120 levels in which failures can be ranked however dealing with 120 levels for thousands of failures types will be time consuming, complex to handle and chances of a failure being placed in the wrong category will be high.

A3. design a failure ranking system that can be applied to all components like electrical, mechanical, electronic and computing, using same scheme. This is essential as use of varied failure ranking schemes for different component types will make the failure ranking scheme complex to implement

A method has been designed in this work that uses a set of 3 high level generic questions (that meets the need of A3) whose responses are restricted to a ‘YES’ / ‘NO’ (that meets the need of A1) to restrict the calculated RPN value to 10 levels (that meets the need of A2). In this scheme, 3 questions are designed individually for Severity, Occurrence and Detection (S,O,D) such that the answer to each question is limited to a 'YES' / 'No'. A value of '2' / '1' is allocated to 'YES' / 'No' response. The individual numerical value for Severity, Occurrence and Detection is obtained by multiplying the responses to their questions. The individual numerical values for Severity, Occurrence and Detection are then multiplied to obtain the value of RPN. As an example, if the answer to the three questions for Severity were (Yes = '2', No = '1', Yes = '2'), the value of Severity will be 4 (=2*1*2). Likewise values for Occurrence and Detection are determined and value of RPN number is calculated. An illustration is given in Figure 3.15 where sample questions designed for mechanical components are shown. The response to these questions will give values of (S,O,D) from which the value of RPN is calculated.

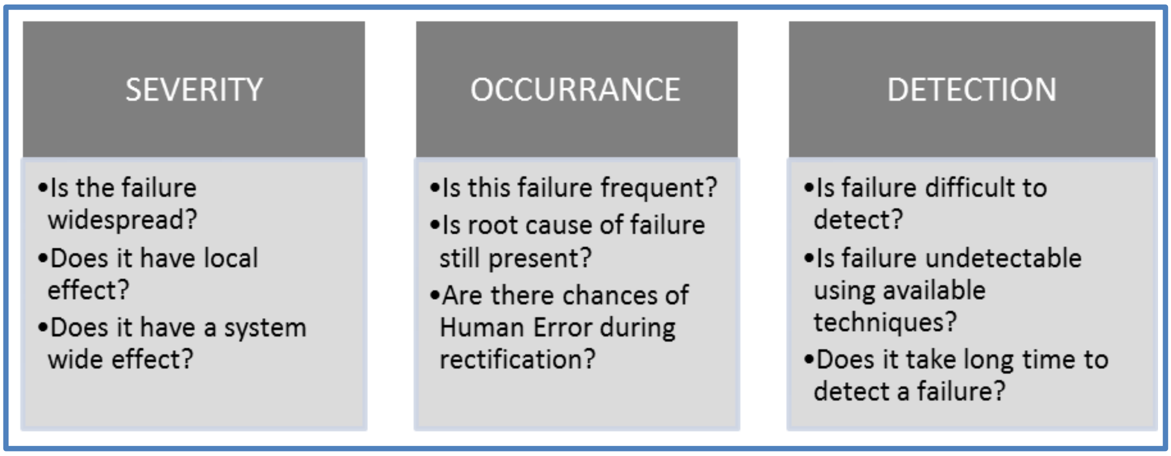


Figure 3.15 Shows the type of questions asked while evaluating value for (S,O,D)

This scheme adheres to the requirements listed in A1, A2 and A3 above and so offer benefits over schemes discussed previously in this work. This is since:

- the maximum and minimum values of (S,O,D) are limited to (8,8,8) and (1,1,1) respectively. This is less than (10,10,10) for the 10 point system but greater than (5,5,5) for the 5 point system used to calculate RPN value. However these limits in the new scheme restrict RPN value from 1 to 512.

- number of levels in the new scheme is limited to 10 (Table 3.10). This is less than the number of levels in the 10 point (120 levels) or 5 point (30 levels) systems. In Table 3.10 ranking of failures in the order of their severity is shown and the required maintenance strategies are indicated.

Level	**RPN Value**	**Comments**
Level 1	1	No Failure
Level 2	2	No Effect of Failure
Level 3	4	Negligible Effect of Failure
Level 4	8	Noticeable Effect of Failure
Level 5	16	Some Effect of failure – May not require maintenance
Level 6	32	Failure needs maintenance but may not be urgent
Level 7	64	Failure requires maintenance at an early date
Level 8	128	Failure has major impact – Result in reduced power – Need Maintenance
Level 9	256	Critical Failure – Reduced power generation – Urgent Maintenance
Level 10	512	Catastrophic Failure – No power generation – Require Major Maintenance

Table 3.10 Shows ranking of failures in different groups according to their RPN value

- answer to questions for (S,O,D) are limited to 'Yes' / 'No'. So the probability of choosing a right answer is 50% that makes the probability of finding the correct value of RPN to be 0.125. This is much higher than that for the 10 point scale (0.001) or the 5 point scale (0.008).
- the questions are designed according to the component and failure type, and so its response directly supports plan better maintenance. This method can be equally applied to any electrical, mechanical, civil or other components.

A demonstration of using FMECA$^+$ and new method of RPN is shown in Table 3.11 for some failures in WT gearbox. Although only few columns are shown in Table 3.12, it shows a comparative analysis of traditional RPN and new system of RPN value calculation. As observed from Table 3.11, the highest RPN values in the two cases are seen for "Excessive Play of Gearbox Mounting" and "Gearbox Housing Adjustment Problem". However general understanding of gearbox operation indicate that higher risk will be linked to "Gearbox Housing Adjustment Problem" than "Excessive Play of Gearbox Mounting".

Sub Assembly	**Component**	Failure Mode	Cause	Traditional (S,O,D)	Proposed (S,O,D)	t- RPN	n-RPN
Bearing	X	Worn	Worn Out, Fatigue	(5,3,6)	(4,2,1)	90	9
Bearing	X	Binding/Sticking	Binding, Sticking, Seized, Jammed	(7,2,4)	(4,2,1)	56	8
Bearing	X	Excessive Play	Worn-Excessive Play	(5,2,7)	(8,1,4)	70	32
Bearing	X	Loss of Lubrication	Lubricant Dried Out	(7,3,3)	(8,1,1)	63	8
Cooling System	Hose	Broken	Broken	(3,1,2)	(2,1,1)	6	2
Cooling System	Hose	Worn	Worn Out	(3,1,6)	(1,1,1)	18	1
Cooling System	Hose	Cracked/Fractured	Cracked/fractured	(3,2,3)	(2,1,1)	18	2
Cooling System	Hose	Leaking	Leaking	(4,1,3)	(2,1,1)	12	2
Cooling System	Pump	Leaking	Leak, Leaking	(2,1,5)	(4,2,1)	10	8
Cooling System	Pump	No Operation	No Transmission, Catastrophic-Failure While Running	(7,3,3)	(8,1,1)	63	8
Cooling System	Pump	Shorted	Short	(5,2,4)	(8,2,1)	40	16
Cooling System	Radiator	Leaking	Internal Leak	(3,3,5)	(2,1,2)	45	4
Cooling System	Radiator	Out of Adjustment	Needs Adjustment/Out of Adjustment	(3,2,8)	(2,2,2)	48	8
Cooling System	Radiator	Needs Replacement	Needs replacement	(3,3,5)	(2,2,2)	45	8
Cooling System	Reservoir	Leaking	Leaking	(3,2,2)	(4,2,2)	12	16
Gears	Hollow Shaft	Seized	Worn Shaft/Keyway, Seized	(8,2,8)	(8,4,1)	128	32
Gears	Hollow Shaft	Cracked, Fractured	Cracked, Fractured	(7,2,7)	(8,4,2)	98	64
Gears	Hollow Shaft	Bent, Dented, Warped	Warped	(7,3,6)	(4,4,4)	126	64
Housing	Bushing	Loose	Vibration, Loose Screw, Misfire	(5,2,9)	(2,2,2)	90	8
Housing	Bushing	Corroded	Corroded, Seized	(1,2,3)	(2,2,2)	6	8
Housing	Case	Cracked, Fractured	Cracked, Vibration Cracked	(7,2,7)	(2,2,4)	98	16
Housing	Case	Out of Adjustment	Out of Adjustment	(5,3,7)	(8,4,4)	105	128
Housing	Case	Broken	Broken, Damaged	(8,2,8)	(4,2,2)	128	16
Housing	Mounting	Excessive Play	Internal Failure, Excessive Play	(7,4,7)	(4,2,8)	196	64
Lubrication System	Motor	Broken	Broken	(3,5,4)	(2,2,2)	60	8
Lubrication System	Motor	Excessive Play	Internal Failure, Excessive Play, No Failure, Excessive Play	(4,2,2)	(4,2,2)	16	16
Lubrication System	Motor	Aged/Deteriorated	Aged, Deteriorated, Leaking Hydraulic Oil, Unserviceable, Aged	(6,3,4)	(4,2,2)	72	16
Lubrication System	Filter	Broken	Broken Damaged, Part Struck	(7,4,3)	(8,2,4)	84	64
Lubrication System	Filter	Cracked/Fractured	Part Struck-cracked	(4,3,5)	(2,4,2)	60	16
Lubrication System	Filter	Aged/Deteriorated	Deteriorated/Aged - Cracked	(3,3,6)	(4,1,2)	54	8
Lubrication System	Pump	Fails during Operation	Catastrophic Fails while running	(3,5,3)	(2,2,1)	45	4
Lubrication System	Pump	Degraded Operation	Degraded	(6,3,5)	(2,1,2)	90	4
Sensors	Debris	Zero or Maximum Output	Catastrophic -Zero or Maximum output	(4,2,5)	(2,4,4)	40	32
Sensors	Oil Level	Degraded Output	Erratic Output, High/Low Value	(6,2,6)	(4,1,2)	72	8
Sensors	Pressure	No Operation	No Function with Signal	(8,2,4)	(4,4,4)	64	64
Sensors	Temperature	Change in Resistance	Low Resistance Value	(6,3,2)	(1,2,2)	36	4

Table 3.11 Shows an example of using FMECA^{+} for WT-COCA (an abridged version)

Although the level of maintenance and cost needed for servicing "Gearbox Housing Adjustment Problem" may be less in comparison to "Excessive Play of Gearbox Mounting" that requires repair / replacement of gearbox, the risk of operating gearbox with adjustment problems is very high as its effect can propagate to other assemblies and result in many more failures in time that will incur higher than expected costs. This shows that the new system for RPN value offer more detailed and fundamental support for ranking failures and their preventive maintenance. This is critical for planning OWT maintenance.

3.9 Using FMECA$^+$ to predict failures

Several observations were made while failures in OWT-COCA components were analysed using the FMECA$^+$ framework. Some of them are:

A1. failures occur as a result of one or many root causes of failure

A2. a root cause of failure can result in more than one type of failure

A3. simultaneous action of many root causes of failure can result in a failure that is different from that obtained when the root causes act individually

A4. a failure is found with more certainty if it is linked to a specific root cause

A5. occurrence of a failure does not guarantee presence of other related failures

A6. failure in one component does not indicate a failure in adjacent components

A7. some failures can have major impact on wind turbine power generation

A8. rectification of a failure may not guarantee solution of other related failures

A9. root causes for a failure arise due to intrinsic defects, changed operating conditions, human neglect, other root causes and failure in other components.

Some conclusions made from above observations are (C1 – C5):

C1. it is possible to correlate failures to their root causes (from A1,A2,A3,A4)

C2. failures may or may not be independent of each other (from A5,A6)

C3. it is possible to correlate root causes to their failures using conditional probability where they relate based on observed failure patterns. When they are unrelated, their conditional probability will equal '0'. (from A4,A6)

C4. failures with severe effect on power generation capability of WT should be rectified at an early date (from A7,A8)

C5. if probability of failures are known, it is possible to map failures and so predict their occurrence (from A9)

A direct consequence of failure analysis using FMECA$^+$ is the ability to anticipate failure if its root cause was known to follow (C1). This can be done either by identifying occurrence of the root cause of failure or changes made in some observed property of the machine. This is shown in Figure 3.16.

Figure 3.16 Method to anticipate failure if its root cause is known

For example surface corrosion is quite common in offshore location. Various sacrificial corrosion inhibitors are used to limit surface corrosion like Anodic Inhibitors, Cathodic Inhibitors, Mixed Inhibitors and Volatile Corrosion Inhibitors. The mass density of these corrosion inhibitors on the surface can be determined using tools like Electrochemical Quartz Crystal Microbalance or Electrochemical Impedance Spectroscopy. If such tools detect that the mass density of corrosion inhibitor is inappropriate, it can be inferred that corrosion would occur in time (Kern and Landolt, 2001). So failure can be detected by observing some property (mass of corrosion inhibitor in this case). The FMECA$^+$ can be used to keep track of these properties over a period of time and hence will be useful in predicting failure in short or long periods of time.

As a general rule, a set containing root causes of failures can be mapped to another set containing failures. Such a mapping can use either 1:1, N:1, 1:M or N:M relationships as in many instances single root cause of failure gives rise to one failure (1:1), while in many instances several root causes can give rise to one failure (N:1). Likewise a single root cause of failure can give rise to many failures (1:M) and many failures can combine to generate root cause for occurrence of other failures (N:M). This relationship is shown in Figure 3.17 where the relationship has been generalised as a (X:Y) relationship. The curved lines on top of the two sets represent the cases where combination of root causes of failure (Set A) and failures (Set B) will result in the generation of other root causes of failures in Set A and other failures in Set B respectively.

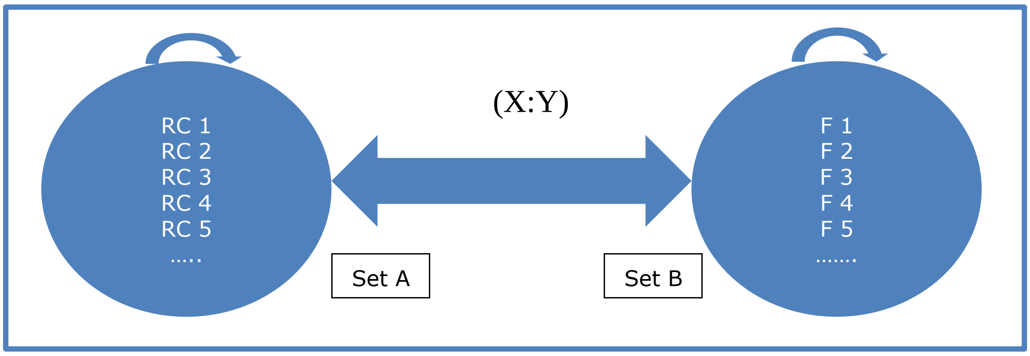


Figure 3.17 Shows of mapping of root cause to their failures (RC=Root Cause of Failure, F=Failure)

For the simplistic case of 1:1 relationship between probabilistically independent root causes of failures and failures, the likelihood of occurrence of a failure (F1) will directly depend on the probability of occurrence of its root cause. This is shown in Figure 3.18 where the probability of occurrence of a failure (F1) is seen to depend on the probability of occurrence of its root cause.

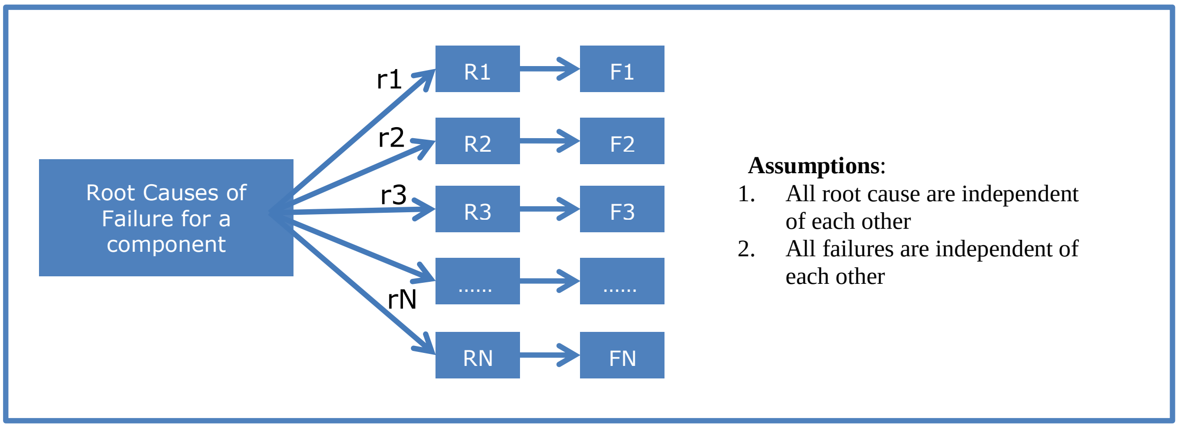


Figure 3.18 Estimating the probability of a failure if root causes and failures are related by a 1:1 relationship

So if r1, r2,….rN refer to occurrence of individual root causes, the probability of occurrence of failure F1 (f_i) is found using Equation 3.1.

$$f_i = \frac{r_i}{\sum_{n=1}^{N} r_n} \quad \textbf{(3.1)}$$

However for practical purposes, the root causes and failures may not follow (1:1) mapping (Figure 3.19) in which case conditional probability is used to predict failures using Equation 3.2 where probability of occurrence of failure (f_i) depends on the probability of occurrence of other conditions, represented by 'E'.

$$P(f_i/E) = \frac{P(f_i).P(\frac{E}{f_i})}{P(f_1)P\left(\frac{E}{f_1}\right)+P(f_2)P\left(\frac{E}{f_2}\right)+\cdots+P(f_n)P\left(\frac{E}{f_n}\right)} \quad \textbf{(3.2)}$$

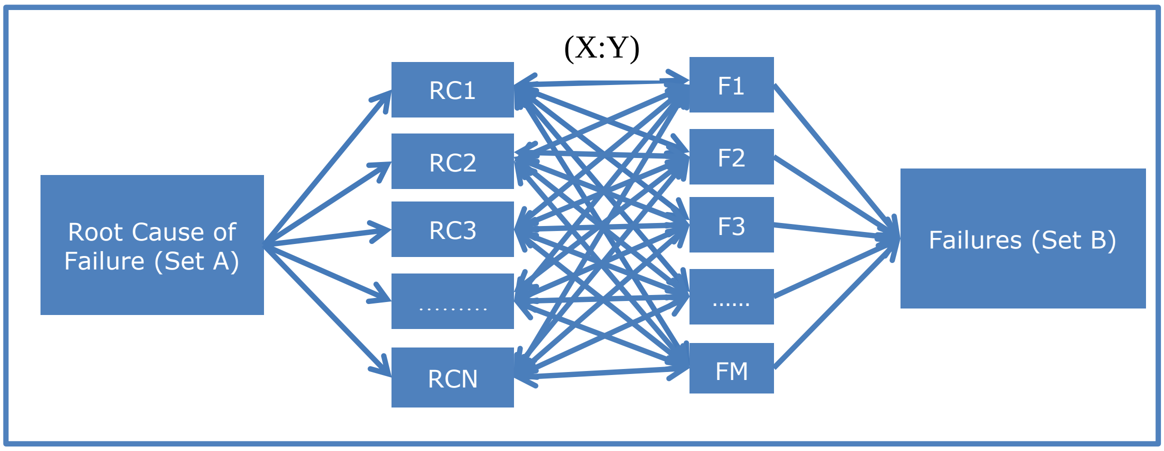


Figure 3.19 Estimating the probability of a failure if root cause and failures are related by generic X:Y relationship

The model shown in Figure 3.19 also benefits from being compatible with Bayes' Theorem that is a derivative of conditional probability. So Bayes' Theorem can be directly applied to establish probability of occurrence of a failure. According to Bayes' Theorem[6], the likelihood of occurrence of an event A, given that event B has occurred, is calculated using Equation 3.3.

$$P(A|B) = \frac{P(A).P(B|A)}{P(A).P(B|A)+P(A').P(B|A')} \tag{3.3}$$

where A' represents the probability when event A does not occur

So probability of occurrence of a failure for a given root cause of failure can be calculated. As an example, suppose that a failure occurs due to two root causes (R_1, R_2) having probability 0.51 and 0.49 respectively. If the likelihood of these failures were known to be 0.1 and 0.65 respectively for the two root causes, the probability that the failure will occur due to root causes R_1 and R_2 are found as:

$$P(R_1|F) = \frac{0.51*0.1}{0.51*0.1+0.49*0.65} = 0.138 \quad ; \; P(R_2|F) = \frac{0.49*0.65}{0.51*0.1+0.49*0.65} = 0.862$$

This can also be applied for the condition when more than one root cause of failure results in failure. This concept can be developed further to achieve C5 (page 88) where Bayes' Theorem can be used to develop Bayesian Networks (Nielsen and Sorensen, 2010). This is shown in Figure 3.20. In the model shown in Figure 3.20, failures are regarded as states that make a transition to another state as a result of influence from root cause / causes of failure. However if no such influence happens, the failure will not make the transition and will stays in its state until serviced. The model shown in Figure 3.20 uses 2 internal causes of failure (intrinsic defect, change in operating condition) and 2 external causes (human negligence and effect of environmental factors) due to which a failure

[6] http://faculty.washington.edu/tamre/BayesTheorem.pdf (Accessed: 11/11/2014)

will make transition to the next state. Here 'C/D' and 'a/b' denotes the conditional probability of failure caused by intrinsic defects and change in operating condition, and human negligence and effect of environmental factors respectively.

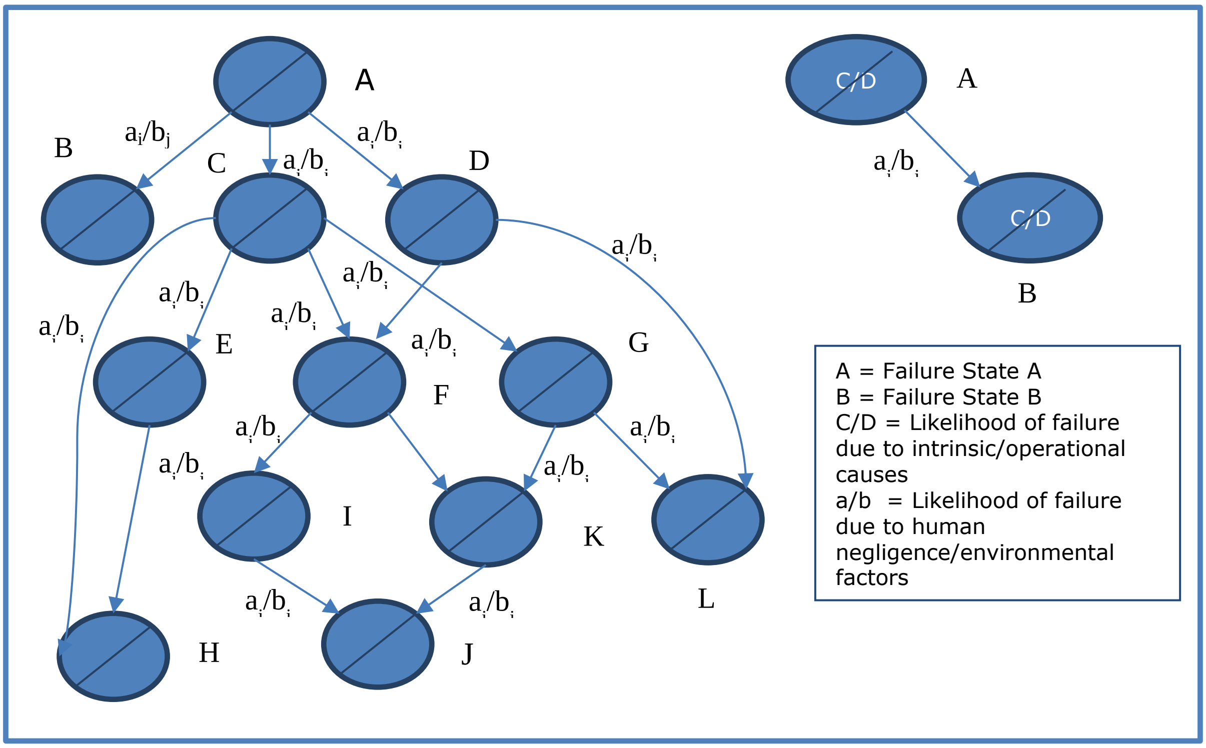


Figure 3.20 Shows a schematic diagram of relationships between failures in OWT components

Although the model given in Figure 3.20 can be verified only when the associated conditional probability values are known, however a simplified version of this model can be used to predict failures in which failures are related to their root causes and such transitions are shown. This is shown in Figure 3.21. A failure makes transition to another failure if the root cause (RC) favours such transition. For example, Failure A makes a transition to Failure B if its RC occurred. However if Failure A was to make transition to Failure G, it can only do so if RC favour transition from Failure A to Failure C, and then from Failure C to Failure G. Unless both of these RC occur, Failure A will not make transition to Failure G. Two examples of this method are shown in Figure 3.22 and Figure 3.23 where failures in bearing and relay have been mapped in accordance to the nature of their root causes of failures.

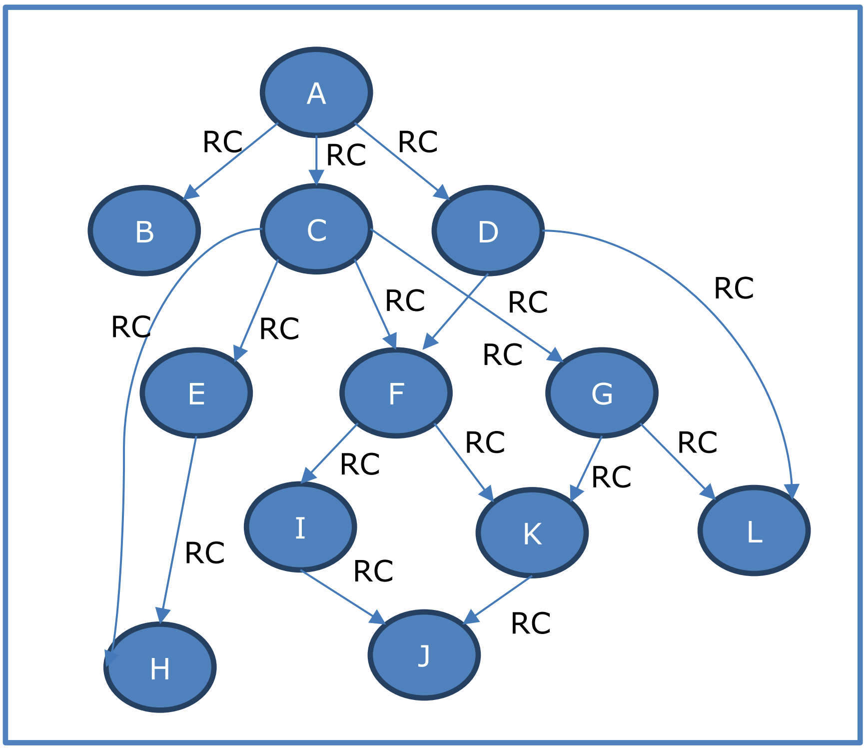


Figure 3.21 Shows a schematic diagram of failures in various states and their transition due to root causes (RC)

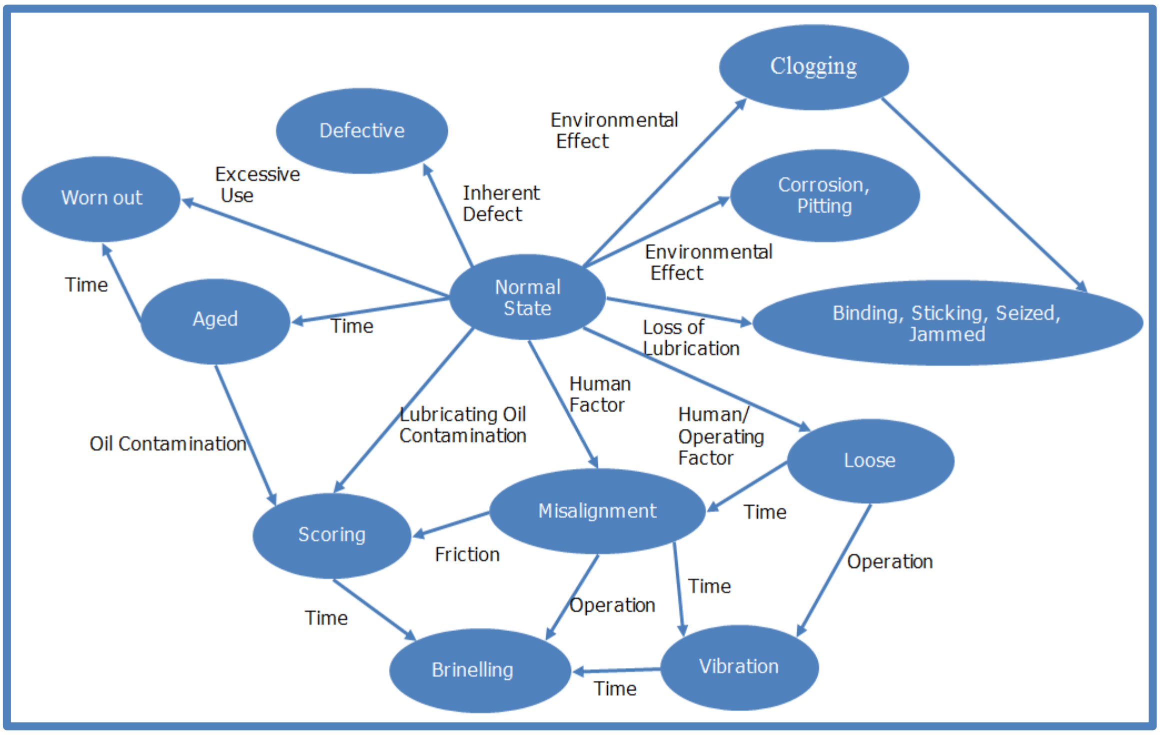


Figure 3.22 Shows the transitions between failures due to various root causes of failures (Example 1: Case of Main Bearing)

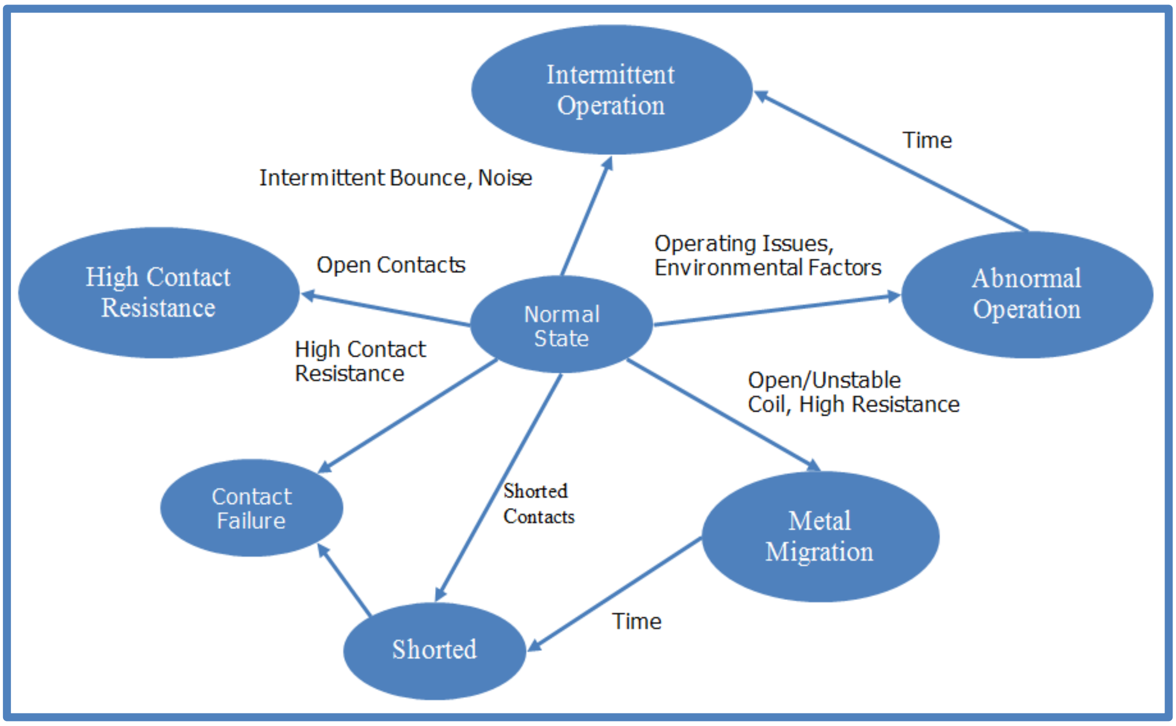


Figure 3.23 Shows the transitions between failures due to various root causes of failures (Example 2: Case of a Relay

As can be observed from Figure 3.23 and Figure 3.24, such figures can be used to identify possible failures in components in anticipation of the occurrence of root causes of failure and hence circumvent failures and faults. For Example from Figure 3.23, if human factors caused misalignment of the bearing, there will be cases of vibration, brinelling and scoring in time for which maintenance can be pre planned.

A distinct advantage of using Failure Analysis Method over other Statistical Methods, like Statistical Distribution method to predict failure, is that in Failure Analysis the root causes of failure are identified and neutralised in maintenance. This improves effectiveness of maintenance and prevents failures develop further into more catastrophic failures which requires more resources and cost higher. Due to benefits, multi-million pound projects are trying to achieve this for OWT[7].

[7] https://www.ieawind.org/task_33.html (Last Accessed - 12/11/2014)

3.10 Analytical Methods to Predict Failures

Several analytical methods exist to anticipate failure in components. Amongst these is the Modelling System Failures where failure is predicted using formula of a statistical distribution pattern whose shape is similar to the historic failure pattern of a component. The parameters of the formula are found using failure data, repair time and resource availability (Turnbull and Alldrin, 2003). For example Andrawus (2008) used 'Weibull Distribution' to model the 'Bath-Tub Curve' type failure pattern for WT assemblies. However studies have shown that the 'Bath-Tub Curve' model is unfitting for failure in all types of components. In stochastic conditions where failure patterns change with time, the parameters used to model statistical distribution pattern will require recalibrations with time. This will result in inaccuracies with failure prediction and result in increased maintenance cost. In fact this can be one of the causes for the persistently high cost of OWT maintenance in spite of technical advancements made in improving the reliability of OWT components. The historical failure patterns of components in OWT are not readily available and so use of statistical distribution patterns is not an appropriate method. So failures need to be determined using current state of the component, like by using condition monitoring data.

This work discusses about an analytical process that is useful to confirm failure in components and also identify potential incipient failures. The use of this method also reduces the need for many inspection/monitoring methods to detect failure in components. As OWT contains thousands of components, the use of this and similar other methods will support cut maintenance cost. In this analytical method to anticipate failures, called as Overall Failure Result (OFR) method, failures in components are categorised as 'No Failure' (Category 0), 'Partial Failure' (Category X) and 'Complete Failure' (Category 1). It is assumed that the result of any inspection or condition monitoring method will fall into any of these 3 categories. This categorisation is shown in Table 3.12 (a). A truth table is shown in Table 3.12 (b) that is used to combine Inspection (/condition monitoring) Results (IR) and so establish the true nature of the failure.

Category (C)	Type of Failure
0	No Failure
X	Partial Failure
1	Complete Failure

(a)

C 1	C 2	Overall Failure Result (OFR) (C 1 + C 2)
0	0	0
X	0	X
1	0	1
0	X	X
X	X	X
1	X	1
0	1	1
X	1	1
1	1	1

(b)

Table 3.12 Shows (a) Categories of failures, (b) Truth table to join Inspection Results (IR)

The logic of the truth table is that if a IR declares complete failure of a component, while a 2nd IR finds that the component has partial failure, i.e. a '1' from first IR and 'x' from 2nd IR respectively, the Overall Failure Result (OFR) of this will be a complete failure. Likewise if one IR declares a partial failure and a 2nd IR declares no failure in the component, i.e. 'x' and '0' respectively, the OFR of this will be a partial failure. Some other results are shown in Table 3.12 (b). This logic is extendable and is also useful to combine results of more than two IR. For example if the results of 4 IR are: 'x, 0, 1, x', the OFR for this result will equate to: (x+0) + (1 + x) = x + 1 = 1, i.e. complete failure. Use of this and similar other analytical methods, will reduce the cost of condition monitoring in OWT. As a generalisation, if a machine was known to have 'M' components and requires 'N' inspection methods each at a cost of 'C_i', the average cost of inspecting the machine will be as shown in Equation 3.4.

$$C = \frac{\sum_{i=1}^{N} x_i C_i}{M} \qquad \textbf{(3.4)}$$

where x_i = number of times inspection 'i' was implemented, C_i = cost of implementing 'i' inspection, M = number of components in the machine, N = number of inspection methods needed for M components

However if the OFR method is used, due to which 'y_i' number of IR methods were only required, the average saving made by using OFR is given by Equation 3.5.

$$C_{Saving} = \frac{\sum_{i=1}^{N} x_i C_i}{M} - \frac{\sum_{i=1}^{N} y_i C_i}{M} \tag{3.5}$$

As an example consider the results of 3 IR as shown in Table 3.14. In this the components are assigned sequential number (M_1, M_2,.....,M_7) starting from either the input side or the output side of the machine. The results of the 3 IR (IR1, IR2, IR3) are as shown in Table 3.13.

	M_1	M_2	M_3	M_4	M_5	M_6	M_7
IR 1	0	1	0	X	0	0	X
IR 2	0	0	0	0	1	X	0
IR 3	X	0	0	1	0	0	0
OFR	**X**	**1**	**0**	**1**	**1**	**X**	**X**

Table 3.13 An example illustrating the process for evaluating OFR (M1 – M7 denote parts of machine)

If these components are unique, ideally they will require 7 different IR to identify failure. However if use is made of the OFR model, it is seen that by using 3 IR it is possible to anticipate condition (/failure) of all seven components. The OFR result shows that components M_2, M_4 and M_5 have completely failed while M_1, M_6 and M_7 show partial failure. The component M_3 is seen to be perfectly healthy. However if components M_2 and M_4, that are adjoining components of M_3, show complete failure, it is more than likely that maintenance of M_3 should be planned. The financial benefit of implementing OFR method in this instance is found using Equation 3.5. If the cost of inspecting M_1 – M_7 components using IR1 – IR7 methods are £1000, £2000, £1500, £1200, £800, £890 and £1200 respectively, the average saving (C_{Saving}) made by using 3 IR instead of 7 IR will be:

$$C_{Saving} = \frac{1 * 1200 + 1 * 800 + 1 * 890 + 1 * 1200}{7} = \sim £\,585\ /component$$

3.11 Case Study

Consider an offshore wind farm with 50 WT in which only the gearbox and generator are monitored for failures. The result of this is shown in Figure 3.24. In Figure 3.24, for visual representation, all observed failures are marked by 'X', any anticipated/predicted failures are marked with Y and components requiring replacement are marked with a 'Z'. As seen, 12 out of 50 OWT show signs of failure and need maintenance.

OWT ID	Failures in Gearbox																			Failures in Generator														
	Bearing			Cooling System			Gear		Housing			Lubricating System				Sensor				Cooling System			Rotor				Sensor			Structural and Mechanical				
	Planet	Carrier	Shaft	Coil	Hose	Pump	Hollow Shaft	Planet Gear	Bushing	Case	Mounting	Hose	Filter	Seal	Pump	Temperature	Pressure	Debris	Oil Level	Cooling Fan	Filter	Hose	Rotor Lamination	Rotor Winding	Resistance Controller	Slip Ring	Temperature	Wattmeter	Encoder	Front Bearing	Rear Bearing	Housing	Silent Block	Shaft Bearing
A3																																		
A6		X			Y		Y										X		Y										Z			X		
A8					Z	Y		X					Z		Y																		X	
A15	Y		Y									X			X							X												
A19																									X				Y					
A22										X										X							Y			X				
A23		Y											Z	Z														X		Y				
A35			X																															
A39					X		Y		Y		X																							
A42									X																		X			Y		X		Y
A46													X	X		X																		
A49		Y	Y							X			Y	X				X												Y	Y			

Figure 3.24 Depicts component level failures in an Offshore Wind Farm
(X= Observed failures, Y = Anticipated Failures, Z= Failure requiring replacement)

If manpower cost is £30/hr, transportation costs is £10,000/day, cost of training manpower is £10,000 and cost of repairing failures including spares is £75,000, and if the trip requires 10 crew members that work 2 shifts in a day (8 hours each) for 5 days, the overall cost of this maintenance will be £159,000. However failures can be anticipated using techniques discussed previously in this chapter (marked by 'Y' in Figure 3.25). If the cost of repairing predicted failures is £12,000 when implemented alongside other maintenance activities while if performed separately require 5 staff members for 3 days and cost £45,000 to repair, its maintenance cost will be £71,200 (assuming use is made of a smaller offshore vessel that costs £5,000/day and training costs £4000). However, if such failures were serviced alongside first maintenance, £59,200 will be saved. If due to maintenance delays such failures resulted in downtime of OWT and incur loss of £45,000, the overall savings made by failure prediction will be £104,200. This shows that significant saving can be made by employing failure analysis to predict failures.

3.12 Organising OWT components using hierarchical codes

A coding scheme for OWT components was proposed by Sinha et al (2013). This scheme uses a hierarchical coding scheme that is similar to the ones used in industries where large number of physical assets is maintained like in a library. This scheme is also in agreement with EU FP7 ReliaWind Consortium strategy that considers WT as hierarchical combination of subsystem, assembly, subassembly and components. The scheme proposed by Sinha et. al. (2013) concatenates the codes of subsystem, assembly, subassembly and components to uniquely identify a component in a WT. This method is shown in Figure 3.25. where WT is given a code 'X', drive train assembly is coded as 'D', gearbox as 'GE', bearing as 'B' and carrier bearing as 'C'. This gives unique code for all.

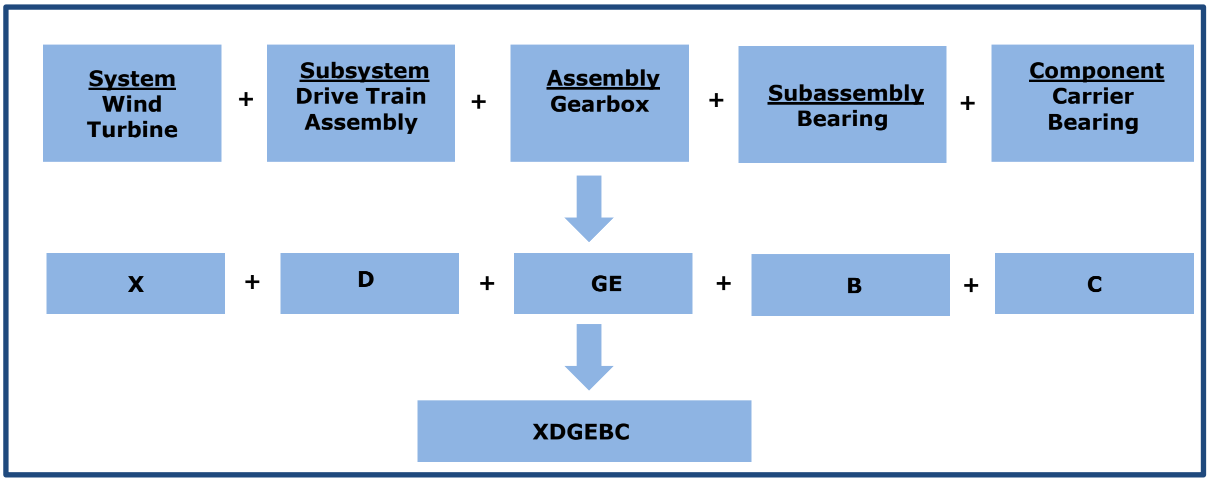


Figure 3.25 A hierarchical naming convention for wind turbine components

For example the code for carrier bearing in the gearbox of the drive train in a WT is 'XDGEBC' while code of the gearbox in the drive train assembly in a WT is 'XDGE'. If two or more items are there at any level, this is denoted by a number alongside its code. For example, the 2^{nd} carrier bearing of 'XDGEBC' is coded as 'XDGEBC2'. The WT code 'X' is substituted by the unique name of the WT in the wind farm. For example the code A15DGEBC refers to the Carrier Bearing in the Gearbox of the Drive assembly of OWT number A15.

This scheme for naming WT components is beneficial as it can be linked to maintenance and failures codes (by suffixing component code with _FXXX or _MXXX) and is useful for identifying components in any WT model. Such a generic naming convention is critical for building a reliability database for OWT which is essential for optimising maintenance and to correctly identify a failing/faulty component while planning for maintenance of a wind farm.

3.13 A modified framework of CBM scheme for use in OWT

With a view to include failure analysis at the centre of planning OWT maintenance, Figure 3.26 and Figure 3.27 show how a CBM for OWT can be planned. The scheme involves making use of condition monitoring data to predict failures and to decide on maintenance. The models proposed in Figure 3.26 and Figure 3.27 offer several benefits. This includes overcoming the complexities associated with statistical method to plan maintenance (where nature of failures is not found). It also effectively manages all types of failures, i.e. failures observed from condition monitoring, failures that are anticipated from condition monitoring data and failures that are predicted from condition monitoring data. The model provides support for detecting failures in real time and using its learning outcomes to train manpower for proposed maintenance. The generic nature of the model implies that it can also be used for OnWT.

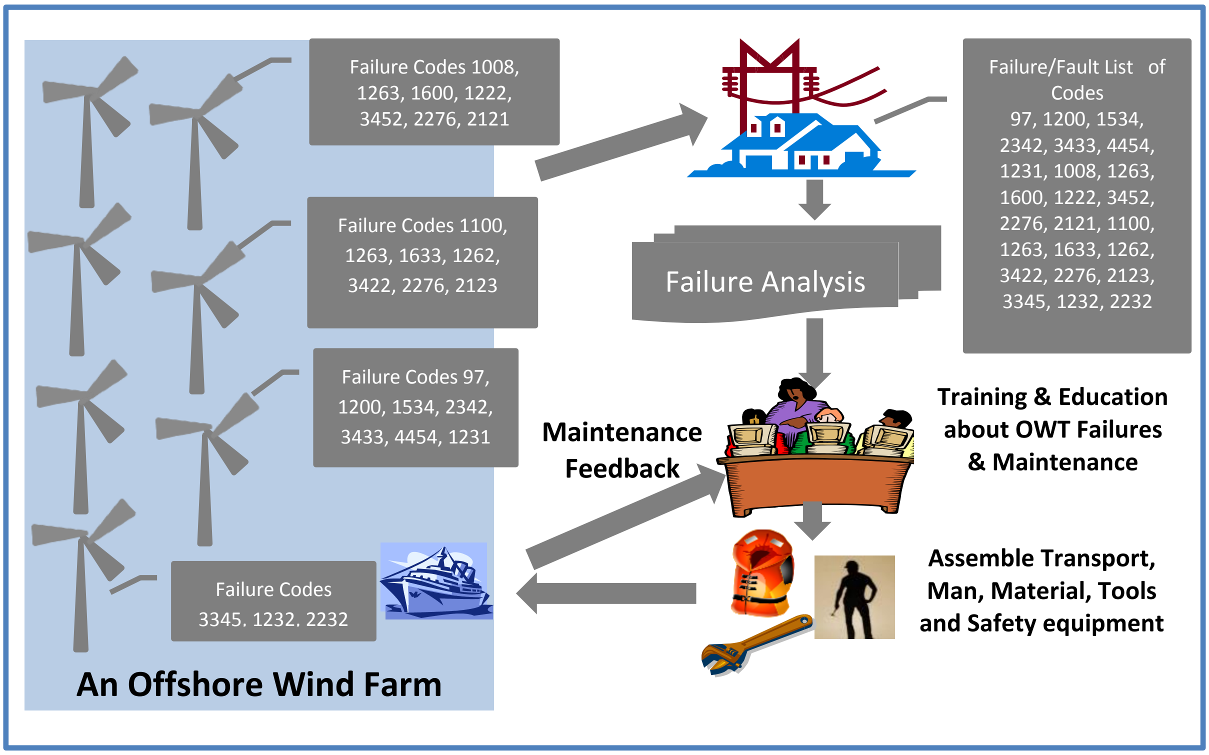


Figure 3.26 Scheme shows the processes involved in planning CBM for OWT

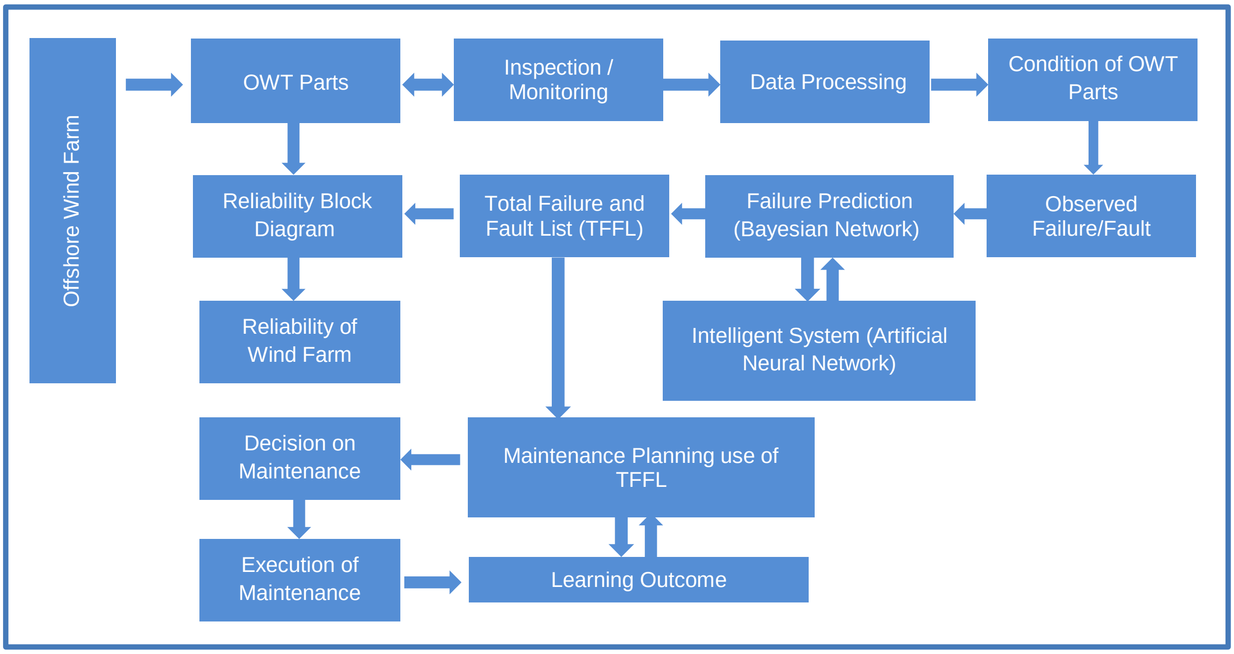


Figure 3.27 A modified scheme for planning CBM for OWT that uses intelligent processes to predict failures

3.14 Summary

The ability to predict failure has profound effect on maintenance cost however using statistical methods to predict failure in machines that operate in stochastic conditions have limitations. Instead use of failure analysis in predicting failure and planning maintenance has benefits as it offers practical benefits. In this chapter the design of a condition monitoring based CBM maintenance scheme was designed. Although this work is fundamental and requires more data about OWT failure in order to make this model more accurate, the chapter also discussed about a moderated framework of FMECA, i.e. $FMECA^+$ that was shown to be useful in predicting failures in different conditions and over short and long time period. This has wider application in planning OWT maintenance and so is critical. A moderated technique to rank failures using RPN number was also discussed. Both of these methods were observed to offer benefits over traditional techniques and are useful in analysing failures, something which is critical for planning economical CBM maintenance scheme for OWT.

CHAPTER 4. Design and Development of OWT-MOT

4.1 Introduction

In Chapter 1, a need was identified to develop systems and tools to support OWT maintenance. It was noted that to comply with ISO 17359, and economise CBM for OWT, there is an immediate need for a tool that can perform component level failure analysis. Such a tool is also useful to predict failures in thousands of OWT components (Chapter 3). When designed to additionally manage OWT resources, such tool will provide the much needed support to maintenance planners to economise maintenance. This chapter discusses about the design and preliminary results obtained from development of such a tool. The importance of developing a reliability database for OWT components is also stressed. The design framework of an Enterprise Resource Planning software package for OWT (ERP-OWT) has also been proposed. This framework is in coherence with the general framework of many existing Enterprise Resource Planning software like SAP and Maximo, however ERP-OWT is dedicated towards meeting the unique requirements of OWT operations and makes use of FMECA^{+} at its core for making maintenance decisions.

4.2 A Reliability Database for OWT

There is a need to design and develop a generic reliability database in which OWT operators can populate their maintenance experiences. This knowledgebase will support predict failures, develop better components, identify root causes of failures, identify critical components, develop maintenance strategies and enable service crew overcome human fallacies during maintenance. Since there are many stakeholders of OWT maintenance, such a reliability database should gather information from and meet the requirements of OWT component manufacturers, service technicians, inspection personal, failure analysts and consultancy firms. However the biggest constraints in designing such reliability database for OWT are (i) extant of the reliability database due to >10,000 component, (ii) variety of standards followed in different parts of the world, and (iii) availability of an adaptable technology that can meet needs of multinational personal, like conversion between different languages, currencies and maintenance standards. Such a tool should also be capable of storing and analysing large volumes of data.

The framework of a reliability database for OWT was proposed in Table 3.5. In this framework failure data was analysed on 14 different avenues and in Section 3.9 it was shown it can be used to predict failures under different conditions. The framework also enables storage of failure data at assembly, subassembly and component levels. It also analyses cost component, as the cost of components and assemblies in OWT ranges from few to hundred thousand pounds, which is unlike other industries.

4.3 Design Framework of Maintenance Software Tool

The design framework of OWT Maintenance Optimisation Tool (OWT-MOT) has been given by Sinha et al (2013). It is given in Figure 4.1 for reference. The design framework of OWT-MOT is seen to be divided in two sections: Software and Database. The database section stores data and processed data (/information) relating to maintenance. This relates to manuals, resources, manpower, vendors, manufacturers, spares inventory and condition monitoring data of components, amongst others. The software section processes the data that is stored in the database and generates output data (/information) that is again stored in the database. It also has a section that performs FMECA of

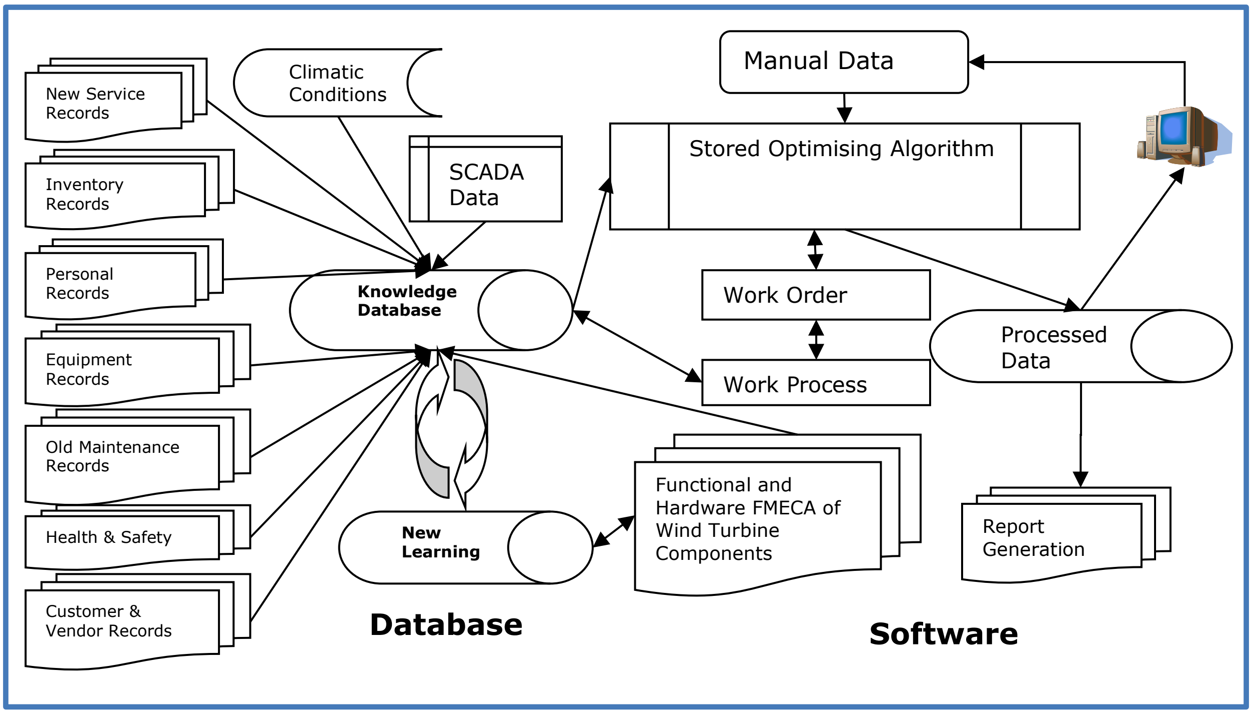


Figure 4.1 Design framework for OWT-MOT software package

WT components that is central to new learnings and a knowledgebase. This uses the FMECA+ framework given in Table 3.6. The framework is designed to meet the requirements of OWT-MOT stakeholders. By consolidating these desires in a single tool, coordination between stakeholders of OWT maintenance will be increased. This will reduces randomness in maintenance management that will invariably economise OWT maintenance.

A more fundamental view of the model shown in Figure 4.1 is shown in Figure 4.2. As seen from Figure 4.2, a tool designed according to stakeholder requirements has many avenues to it. It is complex to design and time taking to implement. As a result this work is more focused on designing and testing some parts of OWT-MOT and on similar lines, other sections can be developed into a software tool as a future work. The block diagram in Figure 4.2 shows the maintenance planning diagram when failure is detected in a gearbox using FMECA+. The FMECA+ framework is used to analyse failures, prioritise them and

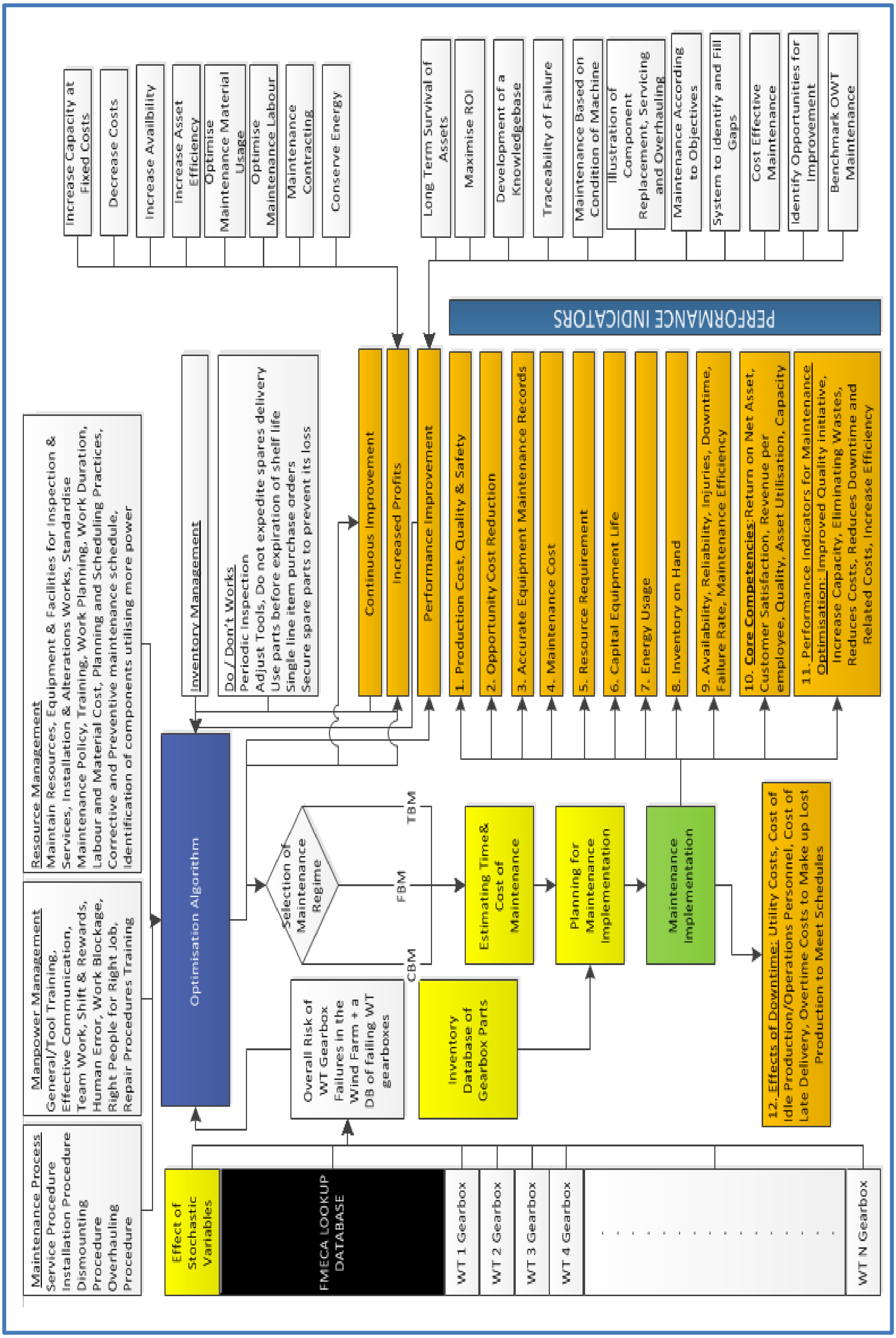


Figure 4.2 Diagram shows an overall framework for the design of OWT-MOT

establish suitable maintenance strategy. This information is fed in optimisation algorithm module to decide on maintenance (discussed in Chapter 5). If the maintenance decision is favourable, information about resources is collected from the database and maintenance is planned in a favourable weather condition. A key feature of OWT-MOT, shown in Figure 4.2, is the Key Performance Indicators (KPI) of maintenance that is incorporated with a view to determine the efficiency of maintenance that OWT-MOT will plan.

Another key feature of Figure 4.1 (stored Optimisation Algorithm), that appears in Figure 4.2 (Optimisation Algorithm), is the decision making module for an optimal OWT maintenance. This Optimisation module is an algorithm that involves identifying optimal condition for planning maintenance given a mix of constrains that governs management, operations, maintenance and monitoring of OWT. These constraints or objective functions have been shown in Figure 4.3. The model shown in Figure 4.2 also considers the stochastic nature of market and environmental conditions and their influence on different modules. Several objective functions, that need optimisation, for management, operations, maintenance and monitoring avenues for OWT business are listed in Figure 4.3. These objective functions are in line with those identified in Figure 2.10 in Chapter 2. A work into making optimal maintenance decision using availability, reliability and productivity has been discussed in Chapter 5. Some common objectives shared between the four modules in Figure 4.3 have also been shown. These include using standardised methods to collect data and report information, optimisation of each of the objective functions and unambiguity between technical and business objectives, i.e. the management should be involved in technical matters and technical people should involve management people in decision making.

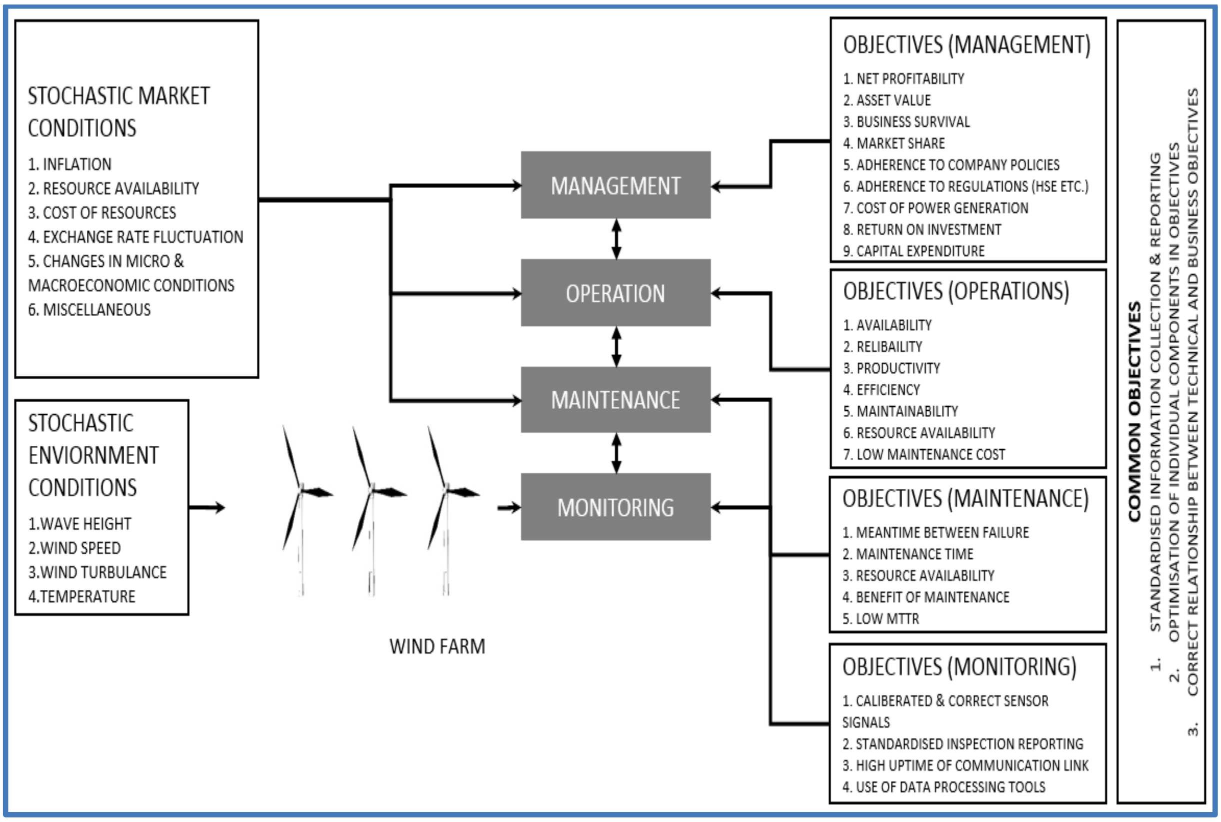


Figure 4.3 Layout of avenues that need optimisation for OWT maintenance

4.4 Design OWT-MOT

In Figure 4.1, the framework of OWT-MOT was seen to consist of Database and Software sections. In Figure 4.4, the design of OWT-MOT database is shown where the overall database is seen to be segmented into 4 parts (Section A - D).

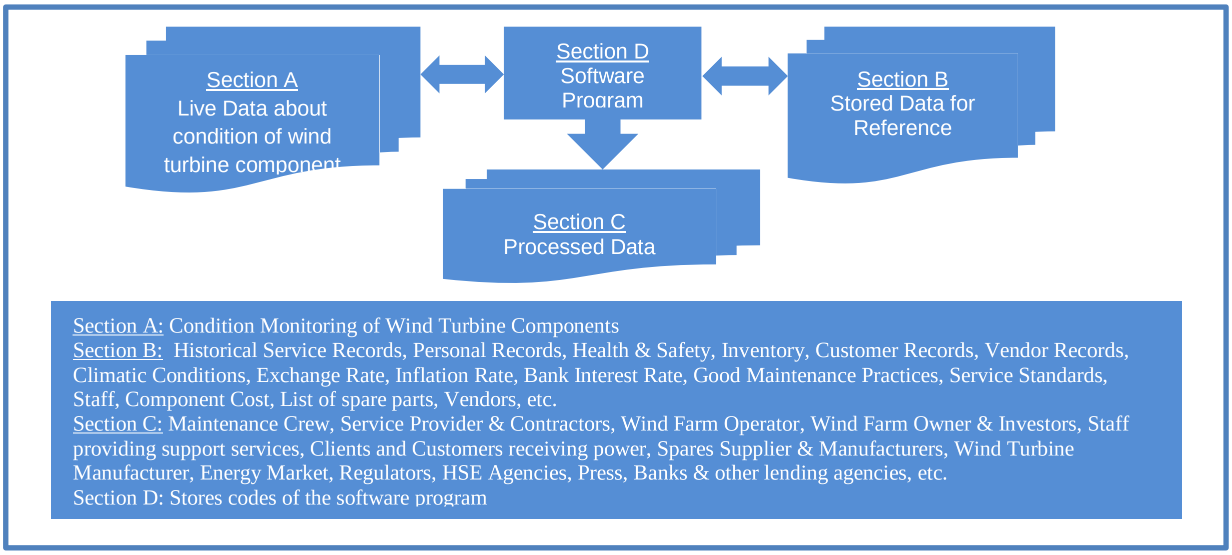


Figure 4.4 Design of database section for OWT-MOT

The segmentation of OWT-MOT database is done according to the need of OWT-MOT and has several benefits. The need to store 'live' SCADA and Condition Monitoring data in OWT-MOT requires an expandable physical database as such data consumes lot of physical space on the database in a relatively small time. It is hence required that such data is separated from other data in the database. As an example, a SCADA system that generates 1kilobyte sized 100 data sets every 10 min interval will generate 288MB/day or 4.3GB/month. If 50 WT were there in the wind farm, their SCADA system will generate 215GB/month. If such evolving data was placed around other data in the physical memory, chances of data corruption will increase. Likewise the software code need to be stored in a secluded segment so that any issues with programming can be easily be rectified. As processed data will generally be interfaced with different output devices, storing such data in different segment has its own benefits. Hence a segmented database will minimise chances of data corruption, ensure data integrity, avoid data redundancies, reduce time for troubleshooting database issues and simplify the process of normalisation of such a database.

4.5 Design of OWT-MOT Database using RDBMS

The concept of relational database was introduced in Section 2.15. It was identified that a relational database is made of tables where data are arranged in rows and columns (Casanova, Furtado and Tucherman, 1991; Date, 2012). The rows, columns and tables in the relational database are related to each other by a relationship, and so the name Relational Database. This approach has benefit over Analytic, Hierarchical and Network type of databases, that are also used to design databases, but for evolving data such strategies become complicated to manage. In addition Relational Database Management System (RDBMS), a software application that supports manage data in a relational database, is available to assist with management of data in the database. This includes insertion, deletion, update and copying of data. As SCADA system outputs are obtained in tabular format, it matches with the layout of relational database in OWT-MOT and makes it easy to migrate SCADA data to OWT-MOT.

The design of a relational database usually involves three steps, i.e. Conceptual Design, Logical Design and Physical Design (Harrington, 2009; Davidson and Moss, 2012) which define the processes encountered in turning the objective of storing data in a database go from the concept phase to physical design of the database. It involves identification of scope, listing of associated variables and parameters, and deciding on their most appropriate arrangement in the physical database. These processes are outlined in Figure 4.5.

Figure 4.5 Steps for designing a normalised relational database

However from OWT-MOT perspective, such a table is complex to build due to the extent of variable and parameters involved and their interdependence. In Table 4.1, lists of various variables and parameters that identify WT components in a wind farm are given. The data types of these variables and parameters are also given. This framework is used to store information about WT components and tag faulty components. This is essential information to correctly identify the failing component amongst thousands of components in a wind farm and plan its maintenance. Such information is also essential for referencing information about wind farm, WT and its components like start and end date of annual maintenance contract, model and manufacturer of components, age of WT, last service date, next service date, amongst other.

Wind Farm	Data	Wind Turbine Assembly	Data	Generator	Data	Frequency C	Data
Wind Farm Name	char	WT ID	Int	WT ID	Int	WT ID	Int
Farm ID	Varchar	Main Shaft Set	Char	Generator SN	Int	Module FC SN	Int
Country	Char	Gearbox	char	Generator ID	Int	FC ID	Int
Location	Char	Generator	Char	Manufacturer	Char	Manufacturer	Char
Onshore/Offshore	Char	Auxiliary Electrical	Char	Model	Char	Model	Char
Distance (KM)	smallint	Control & Communication	Char	Type	Char	Type	Char
Power Rating (MW)	smallint	Frequency Converter	char	Rating	Int	Rating	Int
Farm Developer	Char	**Gearbox**	**Data**	Installation	Date	Installation	Date
Address/Phone	Char	WT ID	Int	Last Service	Date	Last Service	Date
Commission Date	Date	Gearbox SN	Int	Last Overhaul	Date	Last Overhaul	Date
Warranty (Years)	Smallint	Manufacturer	Char	**Main Shaft**	**Data**	**AE Comp Parts**	**Data**
Warranty Expiration	Date	Model	Char	WT ID	Int	Module ID	int
AMC Company	Char	Type	Char	Main Shaft SN	Int	Transformer	char
AMC Period (Years)	smallint	Rating	Char	Main Shaft ID	Int	Circuit Break.	char
AMC Start Date	Date	Installation Date	Date	Manufacturer	Char	Cabinet	char
AMC End Date	Date	Last Service	Date	Model	Char	Fan	char
Wind Turbine	**Data**	Last Overhaul	Date	Type	Char	Fuse	char
Wind Farm Name	Char	**Aux Electrical System**	**Data**	Rating	Int	Prot. Relay	char
Wind Turbine Name	Char	WT ID	int	Installation	Date	Light	char
WT ID	Int	Module SN	int	Last Service	Date	Mechanical Switch	char
Manufacturer	Char	Module ID	Int	Last Overhaul	Date	Pushbutton	char
Model	Char	Serial Number	Char	**Control Com.**	**Data**	Relay	char
Serial Number	Int	Manufacturer	Char	WT ID	Int	Space Heater	char
Installation Date	date	Model	Char	Module SN	Int	Surge Arrest.	char
Cut-in Speed	float	Type	Char	Module ID	Int	Thermal Prot.	char
Cut-out Speed	Float	Voltage Rating	Int	Manufacturer	Char	UPS	char
Swept Area	Float	Current Rating	Int	Model	Char	**Cont Comm Parts**	**Data**
Rated Power	float	Installation Date	Date	Type	Char	Module ID	Int
Gearbox Parts	**Data**	Last Service	Date	Rating	Int	Breaker	char
GB SN	int	Last Overhaul	date	Installation	Date	Temp Sensor	char
C Bearing	char	**Generator Parts**	**Data**	Last Service	Date	Cable	char
P Bearing	char	GN SN	int	Last Overhaul	Date	Contactor	char
S Bearing	char	Filter	char	**Freq Conv Parts**	**Data**	Digital I/O	char
Hose	char	Hose	char	FC ID	int	Bus Master	char
Pump	char	Pump	char	CC Filter	char	Frequency	char
Coil	char	Commutator	char	**Main Shaft Parts**	**Data**	Condition Cab	char
Hollow Shaft	char	Exciter	char	MS SN	int	Data Logger	char
Bushing	char	Resistance Controller	char	Coupling	char	Sensor	char
Case	char	Slip Ring	char	Rotor Lock	char	Power Supply	char
Mounting	char	Core Temperature	char	Trans Shaft	char	CPU	char
Hose	char	Encoder	char	Shaft	char	Comm Bus	char
Primary Filter	char	Wattmeter	char	Axial Bearing	char	Closed Loop	char
Pump	char	Front Bearing	char	Compr Coupler	char	Emerg Button	char
Seal	char	Housing	char	Connect Plate	char	Max Spe. itch	char
Secondary Filter	char	Rear Bearing	char	Bearing Seal	char	Power Switch	char
Debris Sensor	char	Shaft Bearing	char	Main Shaft	char	SC Switch	char
Pressure Sensor	char	Silent Block	char	Radial Bearing	char		
T Sensor	char	Cooling Fan	char	Rotor Lock	char		
				Slip Ring	char		
				HS Sensor	char		
				LS Sensor	char		
				Posit Sensor	char		

Table 4.1 Wind Farm, Wind Turbine and its assembly description

Although the lists provide in Table 4.1 is sufficient to store data for each asset, such database suffers from duplicate data being stored in multiple locations. Such duplication waste physical space in the database and need management. This management of data storage in the database is referred to as normalisation in which tables are linked using Foreign Key where each of the tables is uniquely identified by its Primary Key. This concept is shown in Figure 4.6 where the table 'Wind Turbine Assembly' and table 'Gearbox' are uniquely identified by their primary keys i.e. WT ID and Gearbox SN, but they are connected to each other by a foreign key Gearbox SN, a field that is common in both tables. Such a relationship ensures data integrity in the database and supports development of Entity Relationship (ER) diagram, a database layout diagram (Date, 2012).

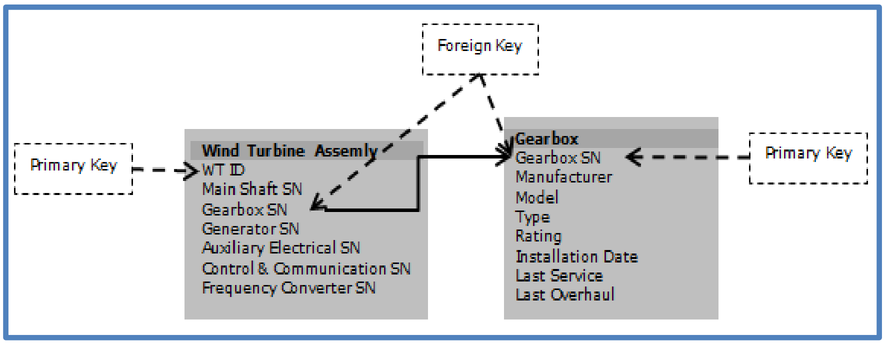


Figure 4.6 Scheme shows difference between primary key and foreign key

The use of primary key and foreign key in managing data in tables shown in Table 4.1 is shown in Figure 4.7. As an example, the table with name OP_Name is connected to tables containing information about wind farms A, B and C using foreign keys WF A, WF B, and WF C respectively. Likewise, information relating to various WT in WF A is related using the foreign key WT 1, WT 2 and WT 3. In this way all the variable of different parameters can be mapped in the database without repeating the data. A data can be recalled using commands and using knowledge of the relationships between tables.

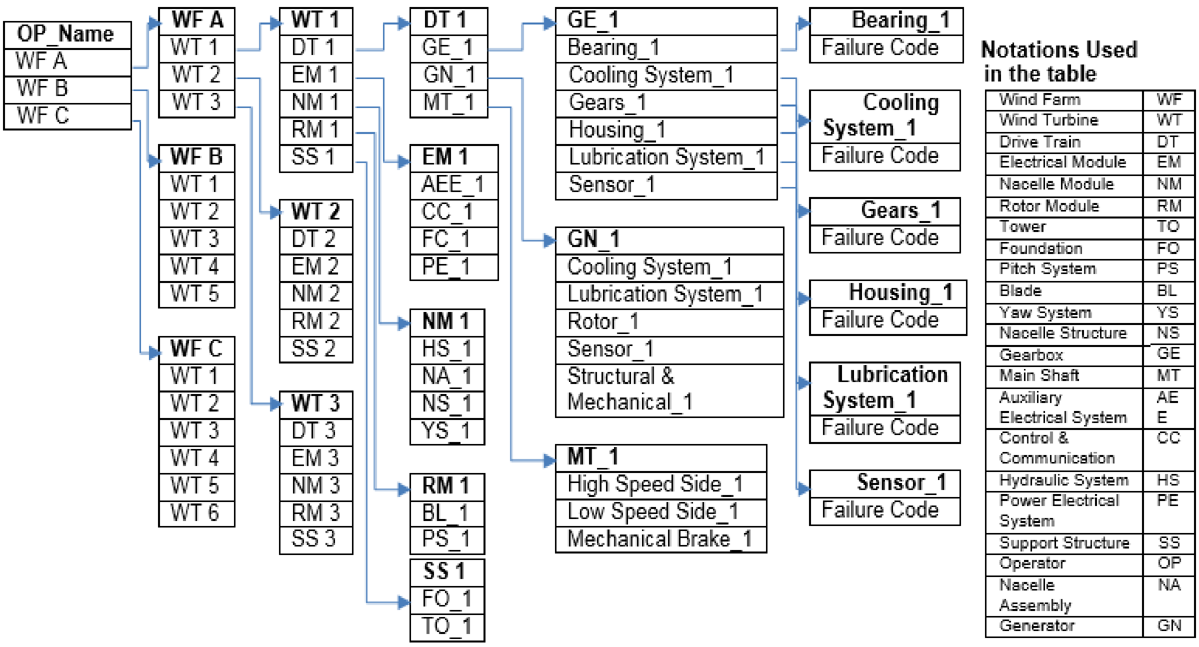


Figure 4.7 Layout of the database when relating tables using 'PK' and 'FK'

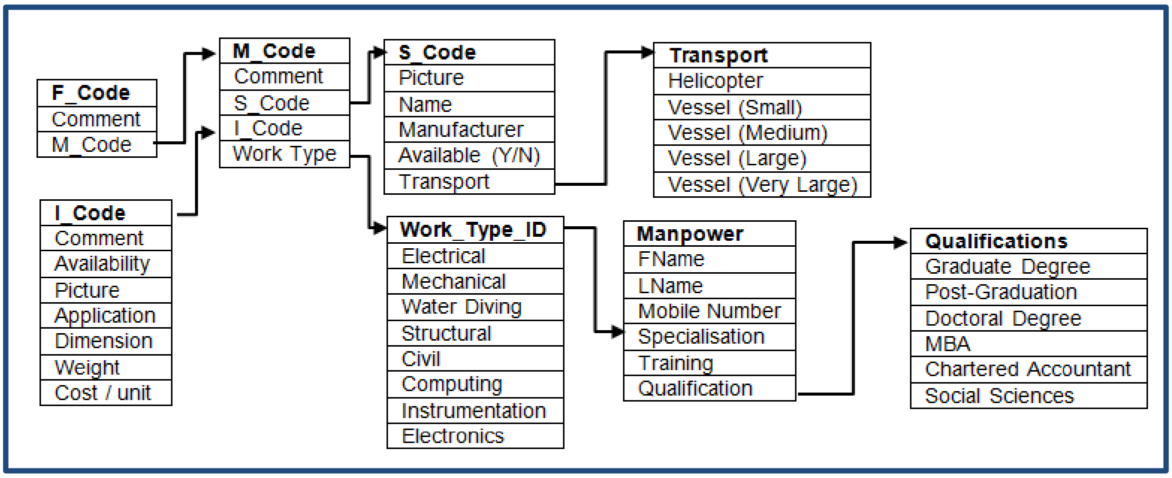


Figure 4.8 Diagram shows role of 'PK' and 'FK' in establishing relationship between tables

The design of database to store condition monitoring and FMECA^{+} data is done using similarly process. The fields of their database are shown in Table 4.2 (vibration analysis, oil analysis and visual analysis) and Table 4.3 (failure database, maintenance database). The information contained in these fields will enable detection and analysis of failures.

Condition Monitoring Technique	Gear Mesh Frequency 2^{nd} Stage	NAS Number	Mg (ppm)	Visual Analysis
CMTID	RMS	Viscosity	Si (ppm)	Component ID
Name of Condition Monitoring	Load	TAN	Fe (ppm)	Inspection Date
Comments	RPM	Water (ppm)	Cr (ppm)	Picture 1
Vibration Analysis	Overall Voltage	ISO Number	Mo (ppm)	Picture 2
Component ID	Oil Analysis	Na (ppm)	Al (ppm)	Picture 3
Record ID	Component ID	B (ppm)	Cu (ppm)	Picture 4
RMS Velocity HSS	Oil Sample ID	Zn (ppm)	Pb (ppm)	
RMS Velocity Gear Mesh Freq Planetary	Inspection Date	P (ppm)	Sn (ppm)	
RMS Velocity Gear Mesh Freq 1^{ST} Stage	Last Change Date	Ca (ppm)		

Table 4.2 Shows tables that store results of Vibration Analysis, Oil Analysis and Visual Analysis

Failure Database	Resolution Method – Isolation
Component ID	Resolution Method – Compensation
Component Failure Mode	Resolution Method – Rectification
Component Failure Type	Severity
Root Cause of Failure	Occurrence
Effect of External Weather	Detection
Effect of Prolonging Maintenance on System Performance	Risk Priority Number
Effect of Prolonging Maintenance on failure	Human Error
Effect of Prolonging Maintenance on Consequence of Failure	Specification Conflict
Effect of Prolonging Maintenance on Downtime	Engineering Error
Effect of Prolonging Maintenance on MTTR	Management Error
Effect of Prolonging Maintenance on Maintenance Cost	Maintenance Database
Future Condition of Failure with Time	Failure Type
Future Condition of Failure with other Failure Causes	Maintenance Steps
Future Condition of Failure due to subassembly	Instruments Needed
Future Condition of Failure due to assembly	Risk to Safety
Future Condition of Failure due to system	Special Skillsets for Job
Resolution Method - Detection	Available Manpower

Table 4.3 Shows specification of Failure Database and Maintenance Database tables

4.6 Managing Software Development – A hybrid approach

There are many methods that outline the process of software development. These methods include Waterfall Development Model, Prototyping Method, Incremental Development, Spiral Development, Iterative and Incremental Development, and Agile Methodology approaches. Primarily these methodologies divide the overall aim of the software development into smaller objectives and follow the cycle of Gathering Requirement, Designing, Implementing, Verification and Maintenance as in the *Waterfall Development Model*. However in *Prototyping Method,* the processes are Determine Objectives, Testing and Implementation. Likewise such processes differ for all models. However each of these methods have distinctive benefits and limitations and in this work a holistic approach for software development is adopted due to the unique nature of requirement of OWT-MOT. In the method adopted for this work into development of OWT-MOT, the fundamental concepts of *Prototyping Method*, *Waterfall Development Model* and *Spiral Development Model* are combined together as shown Figure 4.9. The distinctive feature of this model is that each step of the model performs a designated task in the Design, Development and Deployment environments, referred to here as the 'DDD' model. This is different from the above three models where multiple tasks were performed by each of the steps in the method whereas the DDD model makes the role of each of the modules and their tasks unambiguous. This simplifies the working process and does not create interference between the Design, Development or the Deployment environments.

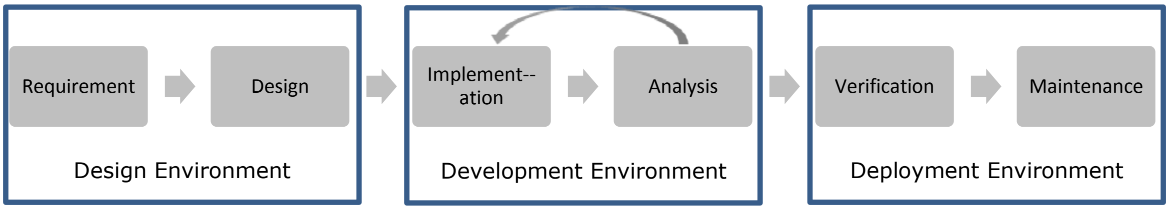
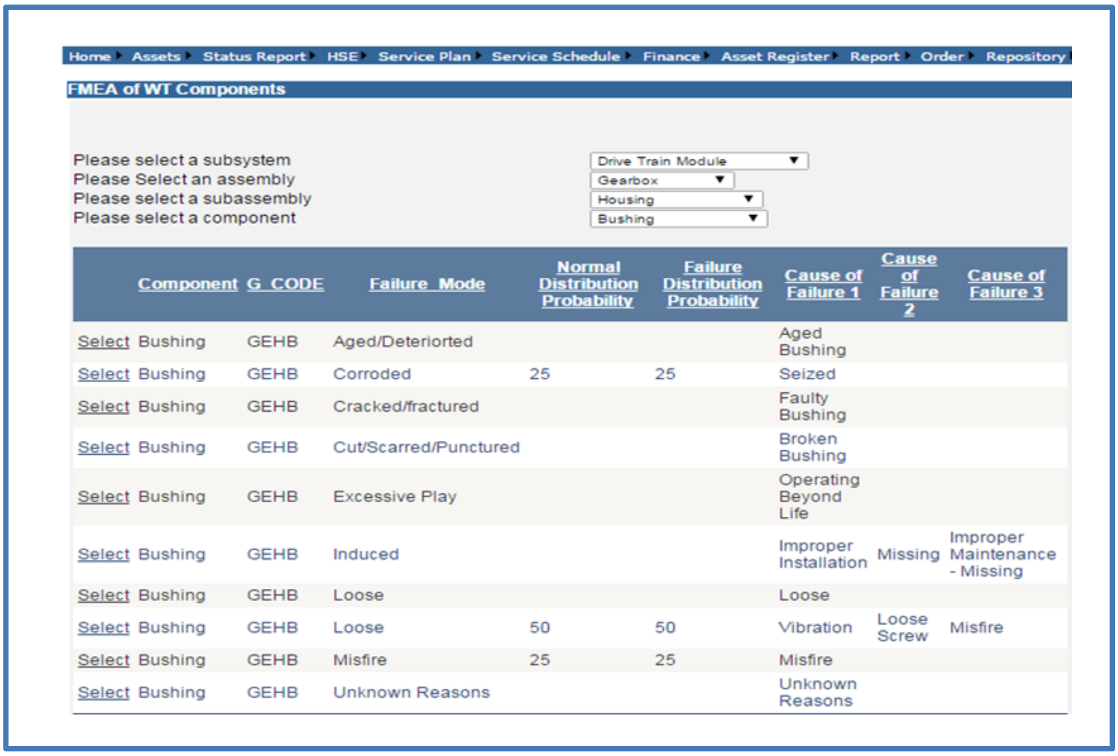


Figure 4.9 Recommended software development framework for OWT-MOT

4.7 A tool to analyse failures and some other results

The need to develop an internet based tool supported by a database that can manage large volumes data was identified by Sinha et. al. (2013). In this work ASP.Net, a software development platform, and SQL, a backend database, have been used to develop OWT-MOT. This has several benefits as an internet based web tool gives easy access to information to all and at all times by using internet. The software has been developed using C# programming language.

In Figure 4.10 (a), Figure 4.10 (b) and Figure 4.10 (c), some results obtained from the development of a FMECA$^+$ failure analysis module for OWT-MOT tool is shown. In Figure 4.10 (a) generic failures in WT gearbox housing bushing have been shown. As seen from Figure 4.10 (a) crack in bushing can arise due to faulty bushing and its performance deteriorates due to aging. Likewise in Figure 4.10 (b) and Figure 4.10 (c) failures and their root causes for hollow shaft and a sample of SCADA data stored in OWT-MOT are shown.


Home Assets Status Report HSE Service Plan Service Schedule Finance Asset Register Report Order Repository

FMEA of WT Components

Please select a subsystem: Drive Train Module
Please Select an assembly: Gearbox
Please select a subassembly: Housing
Please select a component: Bushing

	Component	G_CODE	Failure_Mode	Normal Distribution Probability	Failure Distribution Probability	Cause of Failure 1	Cause of Failure 2	Cause of Failure 3
Select	Bushing	GEHB	Aged/Deteriorted			Aged Bushing		
Select	Bushing	GEHB	Corroded	25	25	Seized		
Select	Bushing	GEHB	Cracked/fractured			Faulty Bushing		
Select	Bushing	GEHB	Cut/Scarred/Punctured			Broken Bushing		
Select	Bushing	GEHB	Excessive Play			Operating Beyond Life		
Select	Bushing	GEHB	Induced			Improper Installation	Missing	Improper Maintenance - Missing
Select	Bushing	GEHB	Loose			Loose		
Select	Bushing	GEHB	Loose	50	50	Vibration	Loose Screw	Misfire
Select	Bushing	GEHB	Misfire	25	25	Misfire		
Select	Bushing	GEHB	Unknown Reasons			Unknown Reasons		

Figure 4.10 (a) Screenshot shows some results obtained from development of failure analysis tool module of OWT-MOT (Gearbox Housing Bushing)

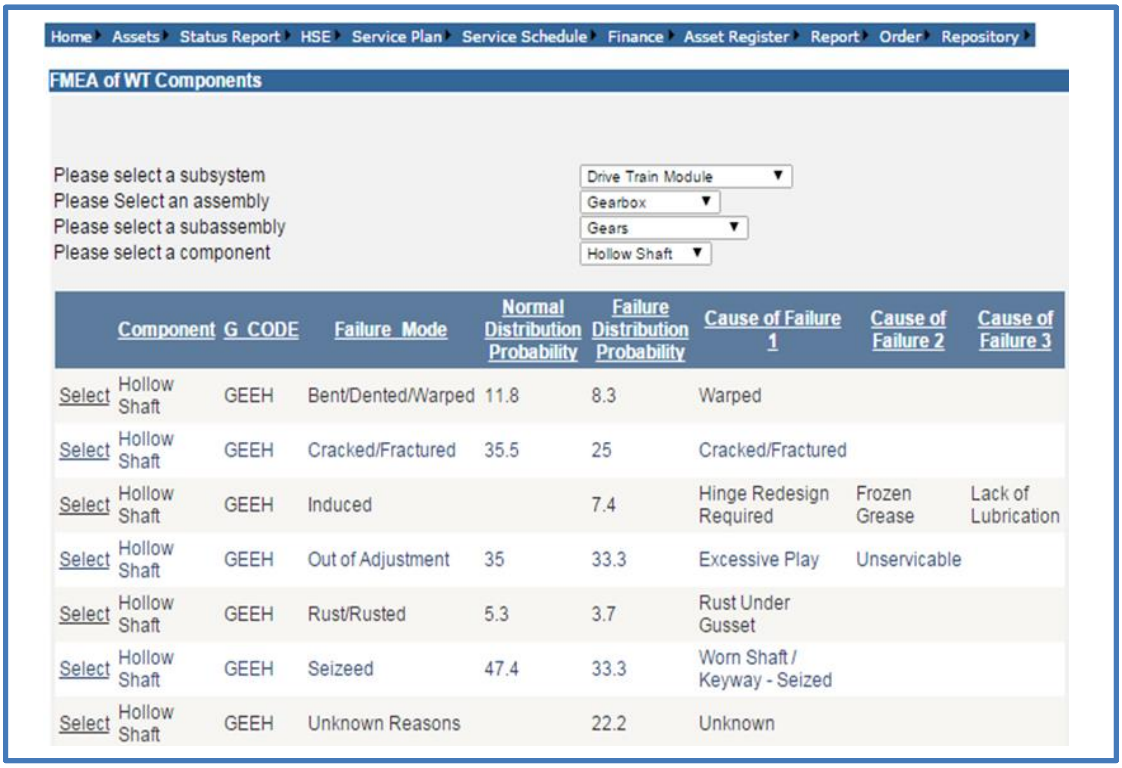


Figure 4.10 (b) Screenshot shows some results obtained from development of failure analysis tool module of OWT-MOT (Gear Hollow Shaft)

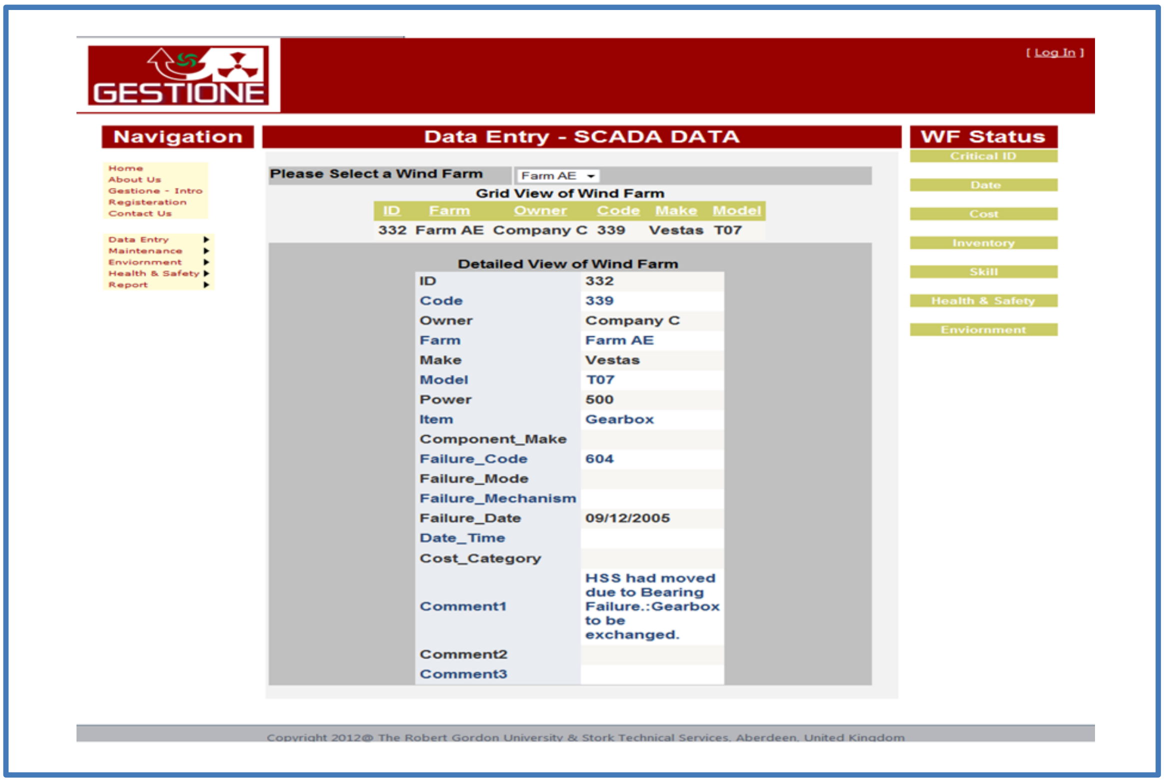


Figure 4.10 (c) Screenshot shows output of SCADA data stored in the database

Some other examples of failure analysis done by OWT-MOT can be seen in Figure 4.11 where the capability to display information about failure distribution for two different instances of failure are shown. It can also calculate the value of RPN number for given (S,O,D) values.

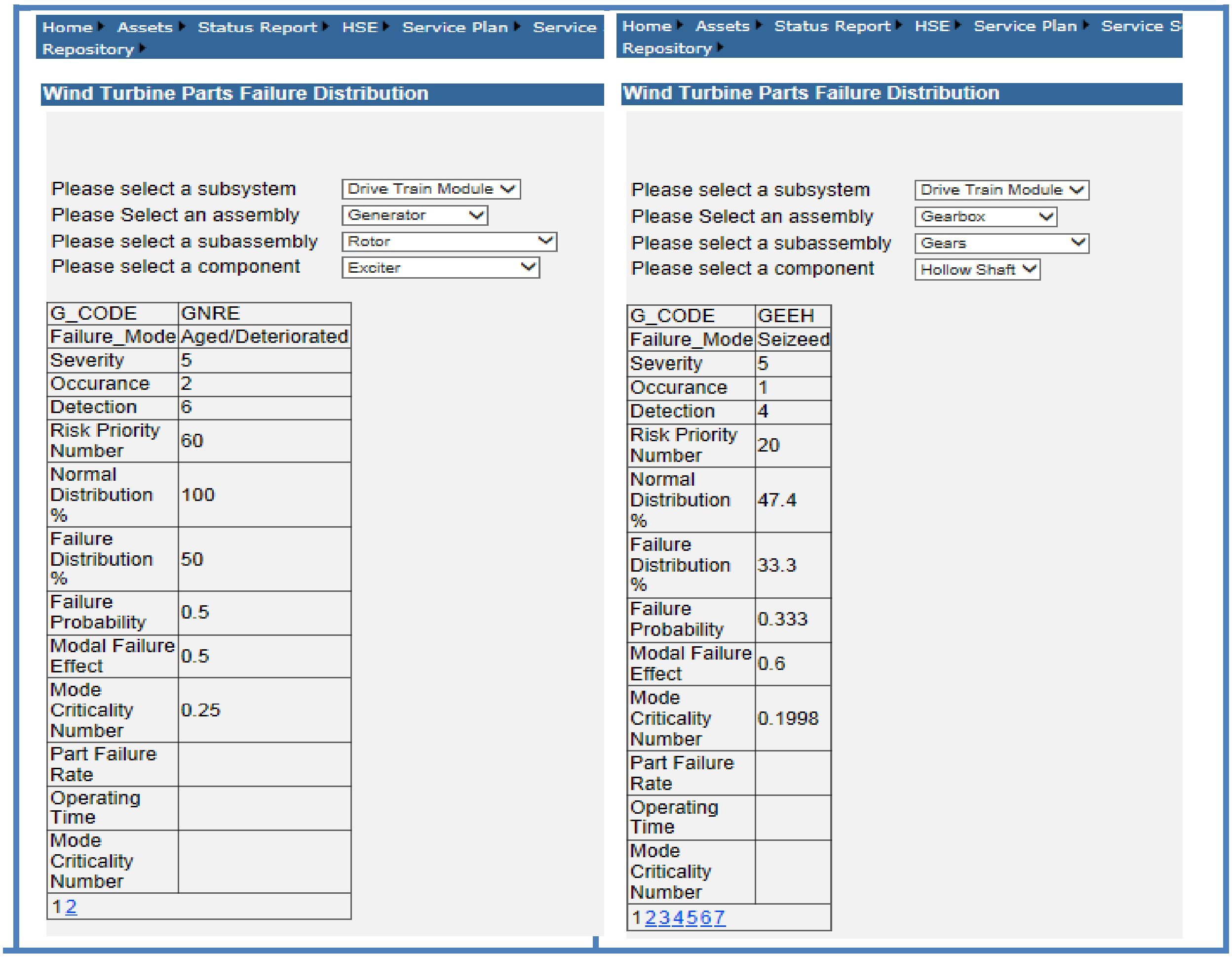


Figure 4.11 Shows OWT-MOT capability to display information about failure distribution for two different instances

Although development of OWT-MOT software package is on-going, an evidence of this is shown in Figure 4.12. In this the OWT-MOT is shown to display the codes of components in OWT using the coding convention that was developed in Section 3.12. Similarly, if the code of a component is known, its associated component can also be determined using the second module shown in Figure 4.12. This is important for referencing information about component and their unique identification while planning maintenance.

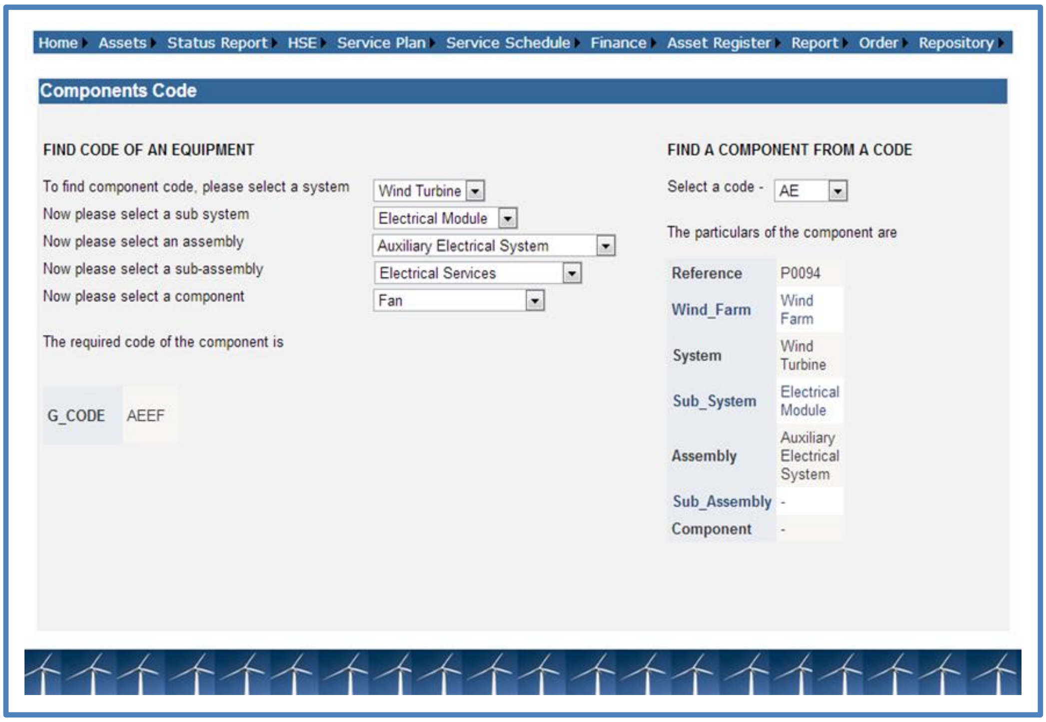


Figure 4.12 Shows the facility to know code of components, or alternatively to obtain information about a component if its code is known

4.8 Design of Enterprise Resource Planning tool for OWT

The concept of OWT-MOT can be extended to integrate other avenues of OWT business and not just to manage OWT maintenance. A tool that integrates different departments and meets requirements of varied stakeholders is often termed as an Enterprise Resource Planning (ERP) software package (Holland, Light and Kawalek, 1999). Such software packages are purposefully designed to meet the needs of various departments and stakeholders like finances, customer relations, customer support, spares inventory, planning and scheduling jobs. Many commercial and open source ERP software packages are available in the market like MAXIMO, SAP, Access Supply Chain, WorkPLAN Enterprise, Tally Solutions, JD Edwards and Transtek however despite their many benefits these packages are not built according to the requirements of OWT. They are also costly to procure (commercial versions), require customisation and operate on licence fees basis. The open source ERP packages are free to use however they still require customisation for OWT use and incur heavy expenses. This also require high level of IT skillsets and a specialist workforce to operate and manage such packages (Holland, Light and Kawalek, 1999) (at £42,500[8] per person/year, a team of 6 people will cost ~£250,000/year). The combined cost of workforce, licence fees, customisation and ancillary services amount to millions of pounds each year that operators may not have provisions to invest such heavy recurring amounts. This makes these software packages costly to procure, implement and manage.

A case study done by Ernst and Young suggests that ERP software provided <50% of potential value of ERP implementation and companies may adopt ERP systems to introduce new systems in the workplace (Holland and Light, 1999) and not exactly to harness its potential. In such circumstances use of ERP systems can have negative impact on an organisation without providing any competitive advantage (Beard and Sumner, 2004) that it wished to achieve. Also, as commercially available ERP packages are mostly generic and customised according to the needs of client, their core functionality may not be suited to the needs and flexibilities with which businesses are accustomed to operate (Kumar, Maheshwari and Kumar, 2003). In such case an ERP package may become a liability and require additional cost to roll back to its original system.

However in spite of such disadvantages studies also suggest that if ERP type software packages are developed according to the needs of its stakeholders and, strategies are developed across the company that encourages use of ERP, significant advantages can be obtained from using ERP packages (Kalling, 2003; Barley, 1990). A similar conclusion has been made in a study by Fosser et. al. (2008) where they highlight the benefits of using ERP system when it is custom made for the business and involves consent of the top management. As OWT industry is multidisciplinary in nature and ERP type software can reduce the

[8] http://www.payscale.com/research/UK/Job=ERP_Consultant/Salary (Accessed: 15/7/15)

complexities involved in managing vast amount of data generated for OWT, it is highly likely that people managing OWT will see gains in using ERP for managing OWT (ERP-OWT). However the challenge for ERP-OWT will be in meeting the requirements of its diverse stakeholders and to link varied business avenues like offshore transport, health and safety, health & safety, information technology, communications, structural engineering, reliability engineering, business analytics, accountancy, service delivery, spares vendors, technology consultants, quality assurance, customer services and delivery, data analytics, business management and others. But OWT is an evolving business and there is a risk that any new system and/or tool may become obsolete with time. So any heavy expenditures on procuring expensive systems and tools should be controlled, like customizing existing ERP software packages for OWT, but instead dedicated tools should be made that will evolve with OWT, like ERP-OWT.

Another key limitation of any exiting ERP software like SAP, Maximo is their generic design architecture that does not have modules specific to the needs of OWT like condition monitoring, planning offshore maintenance, failure analysis and prediction, amongst others. In view of the above, and in accordance to the requirement of ERP-OWT, a model of ERP type software package for OWT (ERP-OWT) is shown in Figure 4.13. The model contains modules like Asset Management, Financial Planning, Prediction Management, Procurement Management, Shareholder Management, Inventory Management, and Analytics and Audit that are in line with other exiting ERP software. However the model also contains modules like Climatic Conditions, Condition Monitoring, FMECA Database, Maintenance Management and Prediction Management modules that are precursors to the development of other OWT centric dedicated modules for ERP-OWT. This makes ERP-OWT both similar and different from exiting ERP.

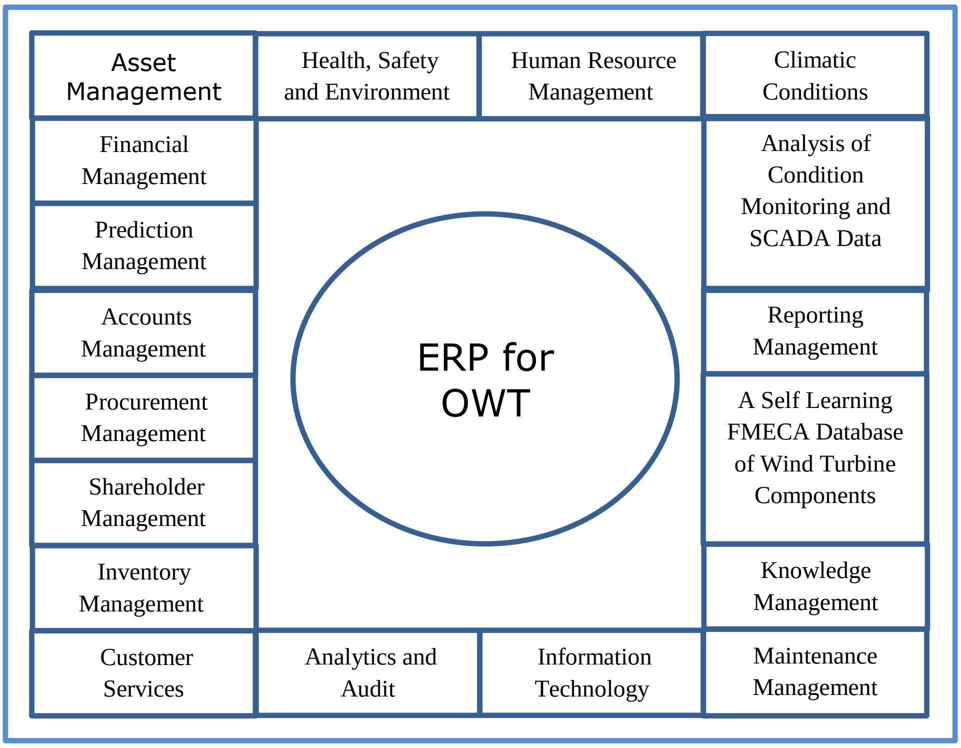


Figure 4.13 Model of an ERP software for OWT application (CM = Condition Monitoring)

The model shown in Figure 4.13 has many avenues to its design and so such work is on-going and forms part of future work of this study. In order to illustrate the extent of this work, the Maintenance Management and A Self-Learning FMECA Database modules shown in Figure 4.13 will contain all elements of Figure 4.2. In addition, the modules associated with Procurement and Inventory Management, and Service Management and Customer Services Management will contain submodules are shown in Figure 4.14 and Figure 4.15. As is seen from Figure 4.14 and Figure 4.15, the submodules for each of the modules contains an extensive list of submodules that all need to be connected with each other while designing the database and software modules of ERP-OWT. In a similar manner, the other modules shown in Figure 4.13 will also have submodules and all of them need to be connected with each other at database and software levels. Although the extent of work required to develop such a tool is huge, procedural steps are being taken to design and develop this tool. Some results of this were shown in Figure 4.10(a)-(c), Figure 4.11 and Figure 4.12.

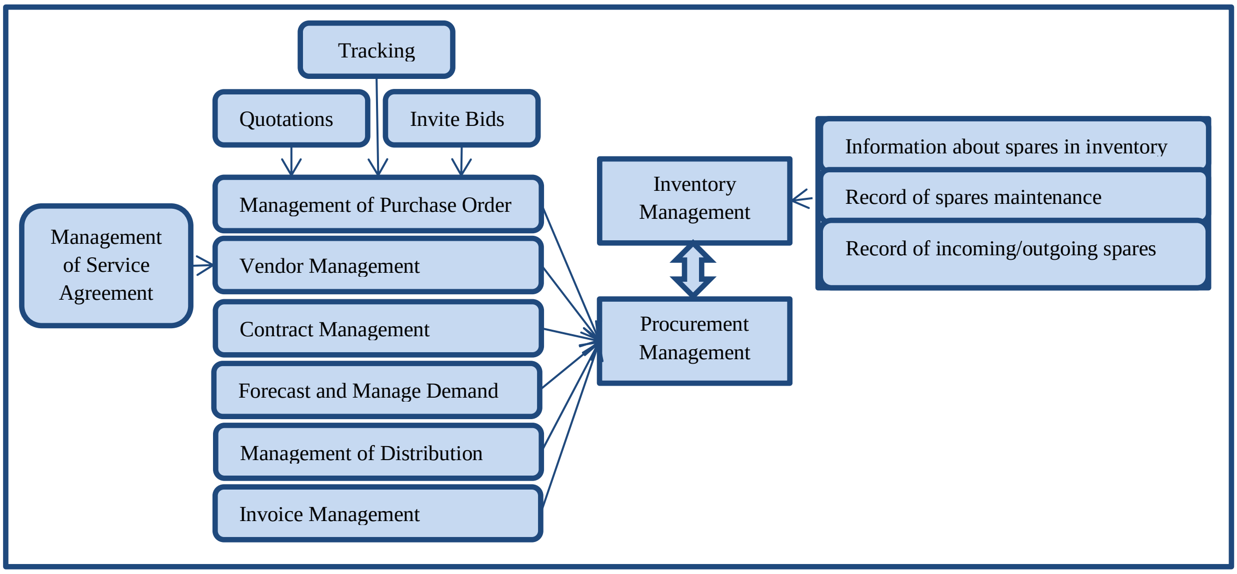


Figure 4.14 Various submodules of Procurement Management (PM) and Inventory Management (IM) modules

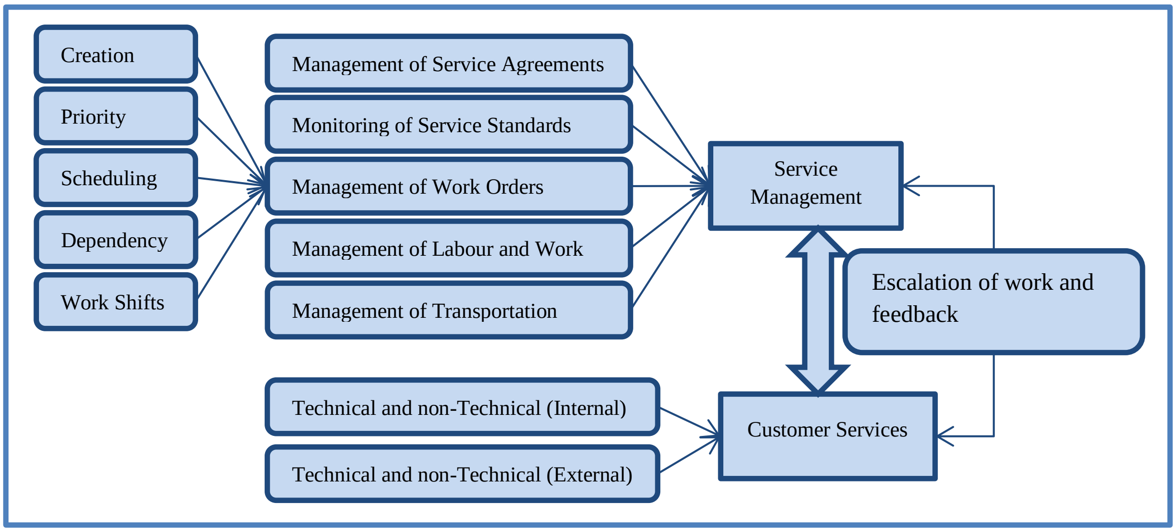


Figure 4.15 Various submodules of Service Management (SM) and Customer Services (CS) modules

4.9 Conclusion

This chapter was focused on illustrating the work that is being done to develop ERP-OWT. In this chapter the design framework of ERP-OWT was shown and it was highlighted that at present work is being done to develop OWT-MOT. Since earlier chapter discussed about the critical need for a tool that can analyse component level failures in OWT, several instances of development of such a tool were shown. The chapter also identified the need to build a reliability database for OWT components and it was shown in Chapter 3 that the $FMECA^+$ framework was useful. As a result, the failure analysis tool was built around $FMECA^+$ framework.

It is anticipated that upon completion, ERP-OWT will provide the much needed support to maintenance planners and business managers to streamline OWT business. This will support use of SCADA system data in failure detection, automatically plan economical maintenance using maintenance optimisation algorithm, show resource availability and, store and analyse the large quantity of data which different avenues of OWT business generates. This will solve a multitude of problems that OWT business is facing at the moment. This will reduce workloads and cut down time for making decisions on OWT operations and maintenance. This will invariable lower the LCoE of OWT.

CHAPTER 5. Decision on OWT Maintenance

5.1. Introduction

The execution of OWT maintenance incurs significant financial expenditures. It is required that models and guidelines are developed to identify conditions when a decision on OWT maintenance will be cost effective. These models and guidelines should be customised to meet maintenance objectives at competitive price and form the backbone of optimisation algorithm discussed in Figure 4.2. A model was proposed by Sinha et. al. (2013) to identify conditions under which maintenance should be planned. A quantitative evaluation of that model from OWT perspective was given by Sinha and Steel (2015 (a)) that gives rise to equations that can be used to make decision on OWT maintenance. This has been discussed in this chapter. The financial impact of using such models in planning OWT maintenance is also discussed.

5.2. A maintenance decision model for OWT

In Figure 4.3, a need was identified to optimise availability, reliability and productivity of OWT from maintenance perspective. A model which addressed these avenues was proposed by Sinha et. al. (2013) that is given in Figure 5.1.

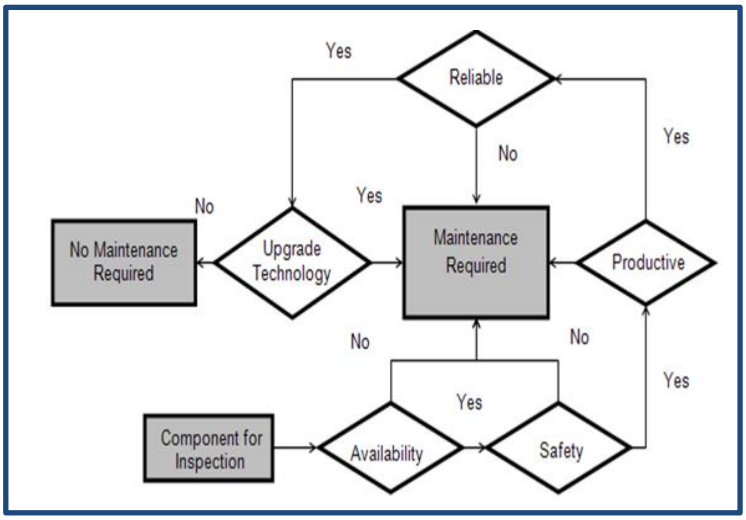


Figure 5.1. A maintenance decision model that identifies avenues for maintenance

In the model proposed in Figure 5.1, avenues relating to OWT's Availability, Safety, Productivity, Reliability and Availability of Upgrade Technology are investigated to decide if maintenance is required. This model is in coherence with condition based maintenance scheme as all avenues shown in Figure 5.1 relate to the condition of components. As an example if a gearbox is diagnosed with failure in its shaft bearing, there will be need for maintenance if, (i) the gearbox was to become unavailable, or (ii) posed danger to the safety of service crew or result in failure of other components in gearbox, or (iii) performance of gearbox falls from its rated value, or (iv) if there is a decrease in the value of reliability of the gearbox. If an upgrade technology could improve availability/performance of the shaft bearing, a maintenance to perform upgrade may be planned. The model given in Figure 5.1 is generic and the sequence of questions can be altered on a case by case basis. As an example, for a standby failsafe component in a machine, whose reliability to operate in critical conditions is more vital, any other question in Figure 5.1 will be superseded by the question on reliability.

Although the qualitative reasoning discussed for model shown in Figure 5.1 identifies avenues on which maintenance decisions should be made, this work performs a quantitative evaluation of that model to derive mathematical relationships which can be used to plan economical maintenance.

5.3. Mathematical Analysis

Some terminologies used in this work have been defined below.

- Availability: Ratio of the time period when an OWT generates power to the total time period in which it could have generated its power.
- *Productive time:* The period of time when wind speed is sufficient to operate an OWT at its rated value, i.e. in between 'cut-in' and 'cut-off' limits

- *Cut-in wind speed*: it refers to the threshold wind speed at which OWT starts to generate power
- *Cut-off wind speed*: it refers to threshold wind speed at which OWT is shut down to mitigate incidences of failure and for generation of negative power[9].

5.3.1 Availability

If 'λ' refers to fraction of time in a year when wind speeds are favourable to operate OWT, and if its value is assumed to be 60% for offshore conditions (Koch and Retzmann, 2010), the productive time in a year for OWT will be 5256 hr/year (= 0.6*365*24 hr). However an OWT may not generate the rated power during its productive time period due to downtime (T_d) or repair works (T_r). So, if OWT operates for T_a (hr) during the 5256 hr/year, Availability (A_O) of OWT is given by Equation 5.1.

$$A_O = \frac{Time\ OWT\ is\ Available\ for\ work}{Total\ Productive\ time} = \frac{T_a}{T_a+T_d+T_r} \tag{5.1}$$

Where: T_a = ∑ time in hours when OWT is available for power generation during productive period of a year; T_d = ∑ time in hours when OWT is unavailable due to failure/fault observed; T_r = ∑ time in hours when OWT is unavailable due to repair works

As an example, if a 2MW (=T_R) OWT was down for 30 days (= 30*24 = 720 hr) during the productive time of a year, either due to failures/faults and/or repair works, Availability of OWT will reduce from 100% to 86.3%. If cost of power generation from OWT is taken as £135/MWh (=C_p) and supposing that the OWT business operates on a profit margin of 25% (=P_P), the total loss incurred due to drop in availability will equate to £243,000(=135*1.25*2*30*24). If 10 such 2MW OWT were down for 30 days in a wind farm during productive time, loss of £2.43million will be incurred. This can be calculated using Equation 5.2.

$$Loss\ (£) = 24\ x\ C_P\ T_R\ N\ (1 + \frac{P_P}{100}) \tag{5.2}$$

Where: x = downtime in days, C_P = cost of power generation, T_R = Turbine rating, N = Number of turbines, P_P= Profit Margin

[9] Above cut-off speed a wind turbine starts to operate like a fan and takes power away from the grid rather than supplying power to the grid. To avoid this condition a wind turbine is shut down at high wind speeds.

A more generalised equation, that uses 'λ' and 'A_o' to calculate loss in a wind farm, is given in Equation 5.3.

$$Loss\ (£) = 8760\ \lambda\ C_P\ T_R\ N\ (1 - \frac{A_O}{100})(1 + \frac{P_P}{100}) \qquad \textbf{(5.3)}$$

However the value of 'A_O', i.e. Availability of OWT, can be increased if downtime and/or the repair time for OWT are reduced (Equation 5.1). Maintenance is used to rectify failures and faults in OWT and so effects availability of OWT. Such maintenance schemes are either failure based, time based or prevention based. However a failure based maintenance and time based maintenance has high values for both 'T_d' and 'T_r', while in a preventive maintenance scheme the values of 'T_d' and 'T_r' are both low, and at times may even equal zero. Such low values of 'T_d' and 'T_r' will support maintain high value of OWT availability. Hence use of preventive maintenance scheme ensures that the value of 'A_o' is improved and that the losses are minimised. However in offshore conditions even preventive maintenance may get delayed due to unfavourable weather or when the required spares are not available in inventory. In such cases a downtime 'T_d' will be introduced that will reduce value of 'A_O' and result in financial losses. So any maintenance scheme for OWT should aim to:

a. reduce downtime (T_d): Use predictive rectification scheme
b. reduce repair time (T_r): improve skill set of personnel, improve prior knowledge on the type of failure and its maintenance requirement
c. perform maintenance as soon as reasonably possible: plan a proactive maintenance scheme

Although the objectives 'a' and 'b' are met by designing a prognostic condition based maintenance scheme discussed in Chapter 3, a decision to plan prognostic maintenance would depend on the technical and financial benefits brought out by such maintenance. This is discussed next.

5.3.1.1 Effect of Maintenance

As a result of maintenance, the original value of Availability (A_O) of OWT is changed to a new value 'Changed Availability (A_C)'. Whereas a good maintenance would increase the value of 'A_C' in comparison to 'A_O', a bad maintenance would decrease the value of 'A_C' in comparison to 'A_O' . Correspondingly such a change can be considered to be either: (i) *Positive Change*: when value of A_C increases, and (ii) *Negative Change*: when value of A_C reduces. If '-e' and '+e' represents the changes made to the value of 'T_a' due to a *Negative Change* and a *Positive Change* respectively, the expression for 'A_C' can be written as,

$$A_{C+} = \frac{T_a + e}{T_a + e + T_d + T_r - e} = \frac{T_a}{T_a + T_d + T_r} + \frac{e}{T_a + T_d + T_r} = A_O\left(1 + \frac{e}{T_a}\right) \quad \text{; Case of Positive Change}$$

$$A_{C\_} = \frac{T_a - e}{T_a - e + T_d + T_r + e} = A_O\left(1 - \frac{e}{T_a}\right) \quad \text{; Case of Negative Change} \qquad \textbf{(5.4)}$$

Based on the magnitude of 'e' in the two cases, the values of A_{C+} and A_{C-} would change accordingly. However if 'e = 0', i.e. maintenance did not have an effect on the availability of OWT, values of A_{C+} and A_{C-} would equal 'A_O' and anticipated losses would inevitably occur. For the case of 'A_{C+}' when the magnitude of 'e' equals '$T_d + T_r$', i.e. maintenance prevented downtime and repair time for a year, then the value of A_{C+} would become '1' and that would be the maximum amount of *Positive Change* that would be possible due to maintenance. So in this case a loss equal to '$24\,(T_d + T_r) C_P\, T_R\, N\,(1 + \frac{P_P}{100})$' is avoided. Assuming a profit margin of 'P_P', planning for a maintenance whose overall execution cost is less than '$24\,(T_d + T_r) C_P\, T_R\, N\left(1 + \frac{P_P}{100}\right)$' is prudent and will bring profit to an operator. Similarly, if the magnitude of 'e' was to equal 'T_a', then the value of 'A_{C-}' would become '0', i.e. a *Negative Change* due to bad maintenance would make the OWT inoperative for 1 year. In such a case, the maximum amount of revenue loss will occur and this will equal '$24\, T_a C_P\, T_R\, N\, (1 + \frac{P_P}{100})$'. So if 10 2MW OWT were out of operation, a loss of £81,000/day or £3375/hr will occur for the wind farm. A plot of Loss (£) verses 'e' is given in Figure 5.2. This figure can be used to estimate loss due to failure and faults in OWT and to estimate the financial gains made due to good maintenance.

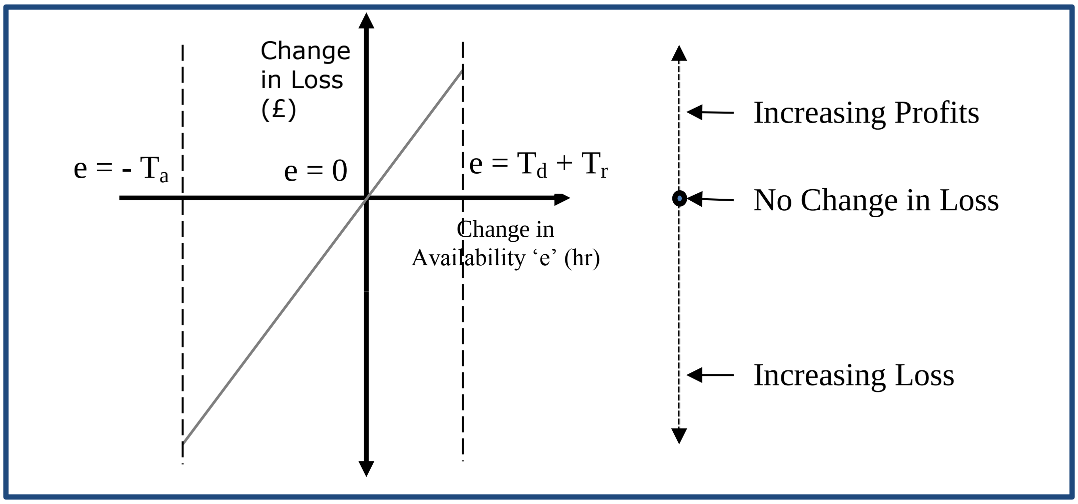


Figure 5.2 Schematic shows variation in loss with changing availability

The extreme points for 'e' are seen to be '$-T_a$' and '$T_d + T_r$' and correspond to the points where maximum loss or profit are made due to maintenance respectively. The effect of maintenance should be considered positive if due to maintenance, the value of 'e' shifts from '$-T_a$' to '$T_d + T_r$' along the line shown in Figure 5.2. This will result in profitable maintenance for a wind farm and its value will increase with the magnitude change in the value of 'e'. Likewise, the effect of maintenance should be considered negative if due to maintenance the value of 'e' shifts from '$T_d + T_r$' to '$-T_a$' along the line shown in Figure 5.2 and this will result in more of expenditures and less of financial benefit from maintenance. So a decision on OWT maintenance can be made using equation of the line shown in Figure 5.2. This equation has been given in Equation 5.5.

$$slope(m_1) = 24\, C_P\, T_R N\, (1 + \frac{P_P}{100}) \qquad \textbf{(5.5)}$$

In order to improve operating profits for OWT, some possible constraints and their solutions have been identified in Table 5.1. The implementation of possible solutions in planning and executing of OWT maintenance will make the overall operation profitable.

Objective	Constraint	Possible Solution
Minimise Downtime (T_d)	Early anticipation of failures	Use techniques to predict failures
	Use existing facilities to detect failures, in order to control costs	Make use of condition monitoring/SCADA data/electrical signals, etc. to detect/anticipate or predict failures
	Use guided failure rectification methods	Build a knowledge base of failures, their rectification methods and steps for rectification
	Early maintenance planning	Early planning improves chances of timely maintenance and so reduces downtime
	Complexity of making decision on maintenance	Decision making by management, administration and safety personal should be simplified to reduce delays in execution of maintenance
	Resource availability	Optimal availability of resources like manpower, tools, transportation, spares, etc. should be maintained
	Failures with high / low downtime	Failures that result in high periods of downtime should be rectified as soon as possible, while minor failures that do not contribute towards downtime should be deferred until next maintenance
Reduce Repair Time (T_r)	Various types of OWT models and rating of components	New technologies that simplify detection of failures and servicing of variety of components in OWT should be encouraged in work place
	Complexity of establishing root cause of failure in components and its neutralisation	Improve skillset of service personal, build and use knowledge bases of best practice for maintenance

Table 5.1 Constraints and possible solutions to reduce impact of downtime and repair time

5.3.2 Productivity

In this work productivity of OWT has been defined as "the ratio of power generated by OWT to its rated power" and is defined for the productive time period only. As OWT generates less power if the performance of its components is not optimal, failure and faults in components should be rectified at an early date. For example if a 2MW OWT generates 1.2MW due to failures/faults in its components, its' productivity will be 60% of its rated value and such reduced power output will result in financial losses and necessitates early maintenance.

Loss in productivity from OWT can occur due to (i) complete loss in power generation capability (due to a major fault), or (ii) partial loss in power generation due to failure in assemblies and components of OWT. Assuming that downtime due to a major fault is 'T_d' (hr) and its repair time is 'T_r' (hr), and for 'k_i' (hr) only 'x_i%' of OWT rated power was generated due to failure/faults in its assemblies and components. The productivity 'P' of a 'T_R' MWh OWT operating for 'T_a' of total productive time period 'T' ($= T_a + T_d + T_r$) is given by Equation 5.6.

$$P = \frac{Power\ Generated}{Rated\ Power} = \frac{T_R * T - T_R * \{\sum_{i=1}^{n} \frac{k_i(x_i)}{100} + T_d + T_r\}}{T_R * T} = \left\{1 - \frac{\{\sum_{i=1}^{n} \frac{k_i(x_i)}{100} + T_d + T_r\}}{(T_a + T_d + T_r)}\right\}$$

$$= \left\{1 - \frac{\{\sum_{i=1}^{n} \frac{k_i(x_i)}{100}\}}{T_a + T_d + T_r} - \frac{T_d + T_r}{T_a + T_d + T_r}\right\} = \left\{\frac{T_a}{T_a + T_d + T_r} - \frac{\{\sum_{i=1}^{n} \frac{k_i(x_i)}{100}\}}{T_a + T_d + T_r}\right\} = \left\{A_O - \frac{\{\sum_{i=1}^{n} \frac{k_i(x_i)}{100}\}}{(T_a + T_d + T_r)}\right\}$$

$$P = \left\{A_O - \frac{\{\sum_{i=1}^{n} k_i(x_i)\}}{100(T_a + T_d + T_r)}\right\} \tag{5.6}$$

In Equation 5.6 a relationship between Productivity (P), Availability (A_O) and effect of partial failures on OWT has been given. It shows that productivity is:

- independent of wind turbine rating,
- directly dependent on Availability of OWT,
- directly dependent on the influence of failures

These statements imply that Productivity of OWT will increase with Availability but reduce if the effect of failures starts to have significant impact on OWT. However mathematically, as 'T' ($= T_a + T_d + T_r$) equal 5256 hr in a typical year, the denominator term of the second quantity in Equation 5.6 will become very large in comparison with the numerator and so the effect of the second term in Equation 5.6 will be insignificant. This means that although OWT productivity is not greatly influenced by few partial failures however if many partial failures were to combine together or result in faults, their effect on productivity may be considerable. So apart from rectifying major failures there is a need to identify and rectify incidences of partial failures in OWT. As partial failures usually arise from incipient failures, there is a need for early detection of failures using novel failure detection methods, tools and techniques. This also shows that the use of Failure Based Maintenance, in which maintenance is planned whenever a minor or major failure is reported, or Time Based Maintenance, where time bound maintenance is planned even if failures are only minor, will be uneconomical and will not change the productivity of OWT. Hence use should be made of predictive maintenance strategies where effects of 'k_i', 'x_i%', T_d and T_r are minimised while increasing the productivity from OWT, a concept that is also known as Total Productivity Management (TPM).

5.3.2.1 Effect of Maintenance

Suppose that due to maintenance, the value of availability 'A_O' changes to 'A_C' while the effect on the failures changes from the initial value of 'x_i%' for 'k_i' changes to 'x_i^-%' for '${k_i}^-$'. So if a failure was completely rectified, value of 'x_i^-%' and '${k_i}^-$' will equal 0. However when maintenance does not completely rectify a root cause of failure, the original value of Productivity (P_O) (Equation 5.6) will change to a value 'P_C' as shown in Equation 5.8.

$$P_C = \left\{ A_C - \frac{\{\sum_{i=1}^{n} \frac{{k_i}^- \, {x_i}^-}{100}\}}{(T_a + T_d + T_r)} \right\} \quad \textbf{(5.8)}$$

A difference between Equation 5.6 and Equation 5.8 is given in Equation 5.9 where it has been marked as 'P*'.

$$Change\ in\ Productivity\ due\ to\ Maintenance\ (P^*) = P_C - P_O = \left\{ A_C - A_O - \frac{\{\sum_{i=1}^{n} \frac{{x_i}^- {k_i}^- - x_i k_i}{100}\}}{(T_a + T_d + T_r)} \right\}$$

$$P^* = \left\{ \frac{\pm e}{T_a + T_d + T_r} - \frac{\{\sum_{i=1}^{n} \frac{{x_i}^- {k_i}^- - x_i k_i}{100}\}}{(T_a + T_d + T_r)} \right\} \quad \textbf{(5.9)}$$

This gives rise to two conditions (i) P^*_+, when maintenance makes an improvement in the value of availability by rectifying faults/failures, and (ii) P^*_-, when bad or delayed maintenance results in more faults/failures in OWT. In these two conditions the value of productivity would increase or decrease respectively. These conditions are shown in Equation 5.10 and Equation 5.11.

$$P^*_+ = \frac{e - \{\sum_{i=1}^{n} \frac{x_i^- k_i^- - x_i k_i}{100}\}}{(T_a + T_d + T_r)} \quad \textbf{(5.10)}$$

$$P^*_- = \frac{-e - \{\sum_{i=1}^{n} \frac{x_i^- k_i^- - x_i k_i}{100}\}}{(T_a + T_d + T_r)} \quad \textbf{(5.11)}$$

However the second terms in Equation 5.10 and Equation 5.11 for P^*_+ and P^*_- will be quite small and so can be neglected. Considering the case when maintenance has a positive impact on productivity, Equation 5.10 simplifies to:

$$P^*_+ = \frac{e}{(T_a + T_d + T_r)} \quad \textbf{(5.12)}$$

As in Section 5.3.1.1 the maximum and minimum values of 'e' were seen to be '$(T_d + T_r)$' and '$-T_a'$ respectively. In accordance to that, a plot of P^*_+ verses 'e' is shown in Figure 5.3. Again, as Equation 5.12 represents a linear relationship between Productivity (P*) and Availability 'e', slope (m_2) of line in Figure 5.3 is:

$$slope(m_2) = \frac{1}{T_a + T_d + T_r}; \quad \textbf{(5.13)}$$

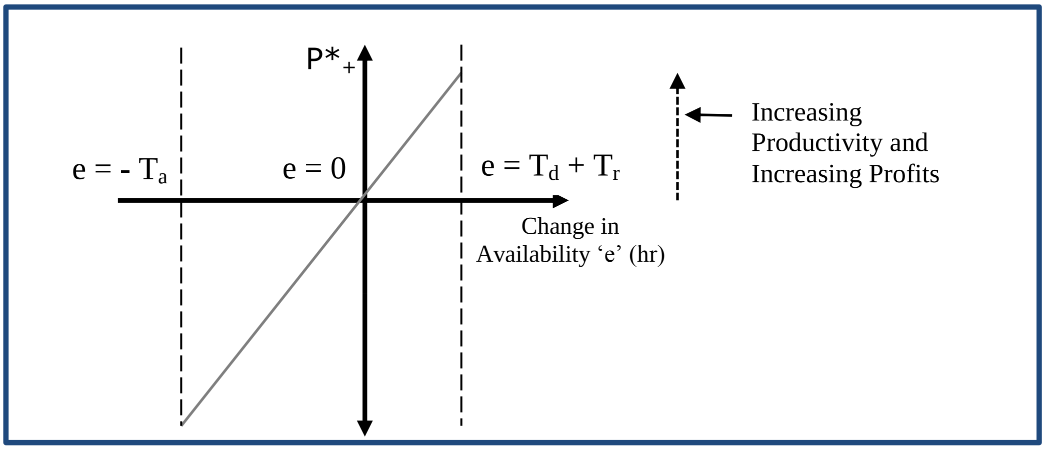


Figure 5.3 Schematic shows variation in productivity change with changing availability

From Equation 5.12, if a maintenance changes the value of 'e' such that it stays along the contour of the line shown in Figure 5.3 and goes from '-T_a' to '$T_d + T_r$', this will indicate a positive change in the value of productivity. In this cases, the minimum and maximum change made in the value of productivity will be given by Equation 5.14.

$$P^*_{+\,min} = \frac{-T_a}{T_a + T_d + T_r} = \frac{-1}{1+\frac{T_d + T_r}{T_a}} \quad \textbf{(5.14 a)}$$

$$P^*_{+\,max} = \frac{T_d + T_r}{T_a + T_d + T_r} = \frac{\frac{T_d + T_r}{T_a}}{1+\frac{T_d + T_r}{T_a}} \quad \textbf{(5.14 b)}$$

Using Equation 5.14 (a) and Equation 5.14 (b), the following can be said about planning maintenance.

(i) $\frac{T_d + T_r}{T_a} \ll 1$: i.e. the combined value of downtime and repair time is less, as in the case of minor failures, in which case maintenance should be avoided

(ii) $\frac{T_d + T_r}{T_a} = 1$: i.e. failure rectification results in productivity to rise by 50%

(iii) $\frac{T_d + T_r}{T_a} \gg 1$: i.e. failure rectification results in productivity to rise by 100%

(iv) The value of P* remains negative in the interval ' $-T_a < e < 0$', and

(v) The value of P* becomes positive in the interval ' $0 < e < (T_d + T_r)$'

Point (v) implies that in order to observe a positive change in productivity from an OWT, its maintenance should only be planned when its failures and faults have a potential of shutting down the power generation capability of OWT for prolonged periods of time, in which case it should be rectified as soon as reasonably possible. As example, let the maximum value of Downtime, Repair Time and Availability of OWT in a year be taken as: T_d = 1440 hr, T_r = 120 hr and T_a = 5256 hr respectively. In order to find the favourable combinations of T_d, T_r and T_a to decide on maintenance, let the above values be divided into four intervals and the mid value of these four intervals are taken to calculate the value of $((T_d+T_r)/T_a)$. These combinations give rise to 64 values of $((T_d+T_r)/T_a)$, amongst which only 9 combinations of (T_d,T_r,T_a) result in $\frac{T_d+T_r}{T_a} \geq 1$. These values are: (900,15,657), (1260,15,657), (900,45,657), (1260,45,657), (900,75,657), (1260,75,657), (540,105,657), (900,105,657) and (1260,105,657). A plot of $'T_d + T_r'$ verses '$\frac{T_d+T_r}{T_a}$' is given in Figure 5.4 where the 9 points have been marked with crosses while the remaining points are marked with dots. The graphical plot makes it possible to establish those combinations of (T_d,T_r,T_a) for which a decision on maintenance decision will be cost effective and so prudent. The financial gain obtained by making changes in the value of productivity due to maintenance can be calculated using Equation 5.12. This value at point '$(T_d + T_r)$' is given in Equation 5.15.

$$Profit\ (£) = 24\ C_P\ T_R N\ (1 + \frac{P_P}{100})[T_d\ +\ T_r] \quad \textbf{(5.15)}$$

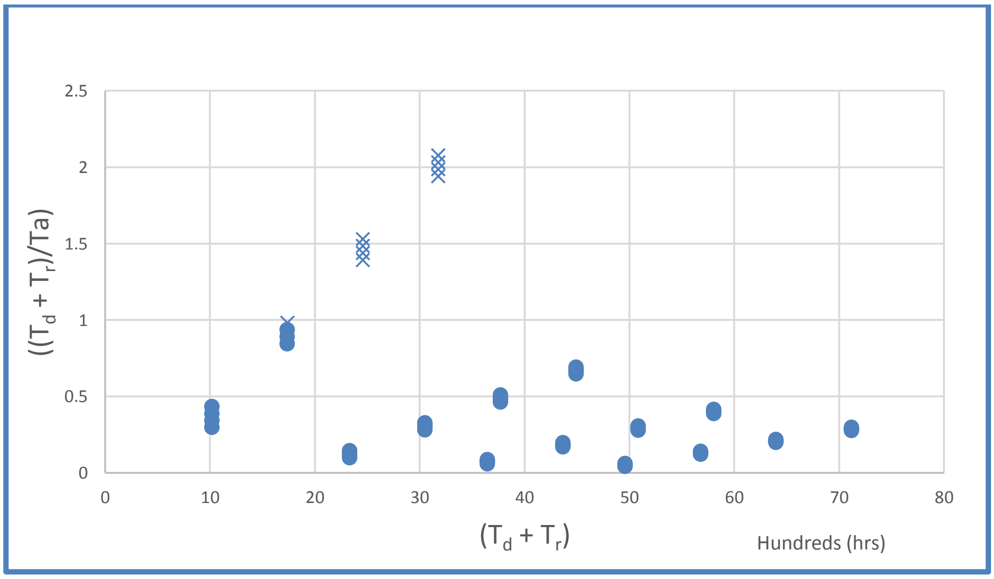


Figure 5.4 Shows favourable conditions when maintenance should be planned (represented by cross marks)

5.3.3 Reliability

Mathematically, Reliability (R (t)) is found using Equation 5.16 where 'f(z)' is the probability density function for failure and 't_1' and 't_2' are the times in between which reliability is determined.

$$R(t) = P_r(t_1 < z < t_2) = 1 - \int_{t_1}^{t_2} f(z)dz \qquad \textbf{(5.16)}$$

The value of Reliability (R(t)) provides a probabilistic view of component's failure. A value of R(t) = '1' denote a healthy component while a value of R(t) = '0' denote an unavailable component. The values in between '0' and '1' denote a propensity towards failure of a component. For example if a component fails frequently, its 'f(z)' value will rise and so its reliability value will reduce. However if techniques are used to detect failure at an early date like condition monitoring, failures can be circumvented. This will lower the value of 'f(z)' and so its reliability value will increase. Reliability of components usually reduces near the end of their useful lifetime. At such times, if value of 'f(z)' is maintained low by using condition monitoring techniques, the overall reliability of OWT for its lifetime can be increased. As low value of reliability results in maintenance activities that have financial impact, condition monitoring techniques can be used for early detection and preventive maintenance of failures that will invariably keep the reliability of OWT high. As failures are caused due to inherent characteristics, use of quality components in OWT is essential to reduce the financial impact of lowered reliability value.

5.3.4 Safety from the impact of failing components

Safety norms are often designed to reduce risk of accidents and/or loss of human life at workplace. Likewise it is essential that components in a machine are protected from the adversities of failing/failed components in their vicinity.

This is because a need to rectify failure in the shortest time possible often results in overlooking the effect which a failed/failing component may have had on adjoining components, subassemblies and assemblies. Such negligence make ground for other failures and result in additional expenditures. There is a need to identify all components whose operation are disrupted by a nearby failing component (MASTER FAILURE) and have a potential of introducing failures (SLAVE FAILURE). While planning maintenance, it is required that maintenance of both MASTER FAILURE and SLAVE FAILURE be planned. A conceptual diagram illustrating this concept is shown in Figure 5.5. For example if the bearing of high speed shaft is known to have cracked (MASTER FAILURE), provision should be made to rectify potential failures in pinion high speed shaft, interface of pinion high speed shaft, gear intermediate speed shaft and the high speed shaft bearing on the rotor side (SLAVE FAILURE) as shown in Figure 5.5.

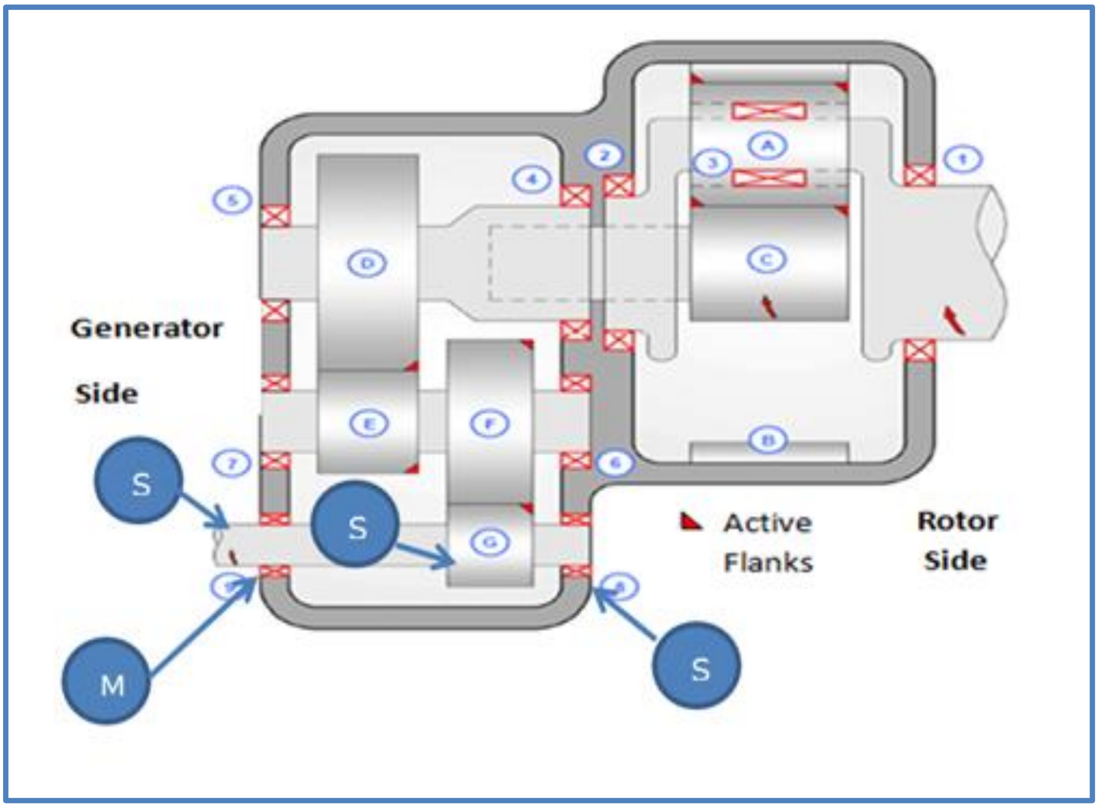


Figure 5.5 Demonstration of MASTER Failure (M) and SLAVE Failure (S) concept (from Figure 3.4)

5.3.5 Upgrade Technology

With recent advancements made in OWT, new upgrade technologies are available that have a potential to improve reliability, availability, productivity and safety in OWT. As OWT is evolving, such upgrade technologies will be made available from time to time however any decision on upgrading OWT need to be based on cost benefit analysis of such upgrade. Mathematically if an upgrade reduced downtime by 'h' (hr) for OWT, the corresponding profit can be obtained by using Equation 5.17.

$$Profit_{Upgrade}\,(£) = 24\, C_P\, T_R\, N\, \left(1 + \frac{P_P}{100}\right) h \tag{5.17}$$

As an example if an upgrade technology reduced downtime of an OWT from 720hr to 700hr in a year, i.e. 20 hr (= h), the availability of OWT will rise from 86.3% to 86.68% (from Section 5.3.1). Using Equation 5.15, this will generate £8.1million/year in additional revenues (P_P = 25%) from the wind farm. If this technology was to benefit OWT for 15 years (lifetime of OWT = 20 years, warranty period = 5 years), the total additional revenue that will be generated from this upgrade will be £121.5million. If the company's operating margin is 70% (operating margin is percentage of profit that is made by spending on an upgrade technology which includes procurement, installation and maintenance of the upgrade technology), an upgrade technology that costs £36.45million will be considered to be a good investment.

The acceptable cost of upgrade technology ('x' (£)) can be found using Equation 5.18.

$$\mathrm{X}\,(£) \leq 24\,(1-\beta)\,\tau\, C_P\, T_R N\,(1 + \frac{P_P}{100})[h] \tag{5.18}$$

Where, 'β' is the operating margin, 'τ' the remaining number of years of OWT operation

For example if there is an issue with the control system software that on average requires 20 of the 50 (=N) 2MW (=T_R) OWT to be switched off for 2 days (h = 48 hr) each year for repairs and testing. If the wind farm operates on a profit percentage (P_P) of 25% and an operating margin of 70%, the acceptable cost of such an upgrade applied for 15 years of the remaining lifetime of OWT can be calculated using Equation 5.18. As seen from below, the acceptable cost of software upgrade will need to be £35million.

$$X\ (£) \leq 24\ (1-\beta)\ \tau\ C_P\ T_R N\ \left(1+\frac{P_P}{100}\right)[h]$$

$$= 24 * (1-0.7) * 15 * 135 * 2 * 20 * (1+0.25) * 48\ =\ £\ 35 million$$

5.4. Summary

A decision on OWT maintenance incurs heavy financial investment and if such investments are not judicious, the operating cost of OWT becomes very high. With a view to rationalise decision on OWT maintenance, models and mathematical equations are required to support maintenance planners make decision on OWT maintenance. This chapter introduced such a model and derived its related mathematical equations. The model identifies availability, productivity, reliability, safety and upgrade technology as key areas around which maintenance decisions are based, and correlated them from OWT perspective. It was seen that both qualitative and quantitative analysis of this model was possible and by making use of the suggested generic formulae, the cost associated with time based and failure based maintenance schemes are controlled. The use of such and similar models, and associated formulae, can control frequent randomly planned offshore based maintenance activities. These and several other related concepts are being incorporated in the optimisation algorithm of OWT-MOT (Figure 4.2) that is being developed as part of ERP-OWT software package.

CHAPTER 6. Summary and Future Works

6.1. Introduction

This chapter summarises the key points of this study, identifies areas for future work and ends with remarks.

6.2. Benefit of this work

This work identified Gearbox, Generator and Electrical System to be the critical assemblies of OWT. This was found from the viewpoint of maintenance cost, spares cost, failure downtime, failure frequency and criticality for operation. It is evident from literatures that statistical methods are primarily used to predict failures and plan maintenance of wind turbines. However statistical methods do not ascertain the nature of component level failures which is critical for planning maintenance. Instead a failure analysis based maintenance scheme has been used in this work that overcomes such limitation and improves preparedness to deal with failures. The role of FMECA$^+$ was found to be central in analysing failures and establishing their root causes. It was also found useful in identifying the effects of a failure on other components and the consequences of maintenance deferment over small and long time periods. However a major benefit of FMECA$^+$ is the scalability of its framework that can store maintenance related information of WT at the component level and analyse it on over 40 parameters. This is essential for planning maintenance and controlling costs. It can also identify components affected due to failures in nearby components, something which in normal situations may get unnoticed. All these aspects have a direct impact on controlling the time and cost required to repair components and to reduce WT downtime. As these avenues directly influence the availability and productivity of OWT (Section 5.3.1.1), use of FMECA$^+$ framework is useful.

The importance of condition monitoring and use of SCADA system data to determine failures and faults in WT assemblies were shown using case studies. It was seen that an intelligent analysis of such data results in information about failures/faults in WT components and their nature. However to make greater use of this data source, it is required that relationships between such data and their indicative failures/faults in WT components are stored in a database. Such a knowledgebase will support maintenance planners in improving availability and reliability of OWT and its components.

The design and development of a FMECA$^+$ based failure analysis and maintenance planning software tool was discussed in Chapter 4. Such tools have a wider utility than just meeting the requirements of maintenance planners and decision makers. As a result, the concept of OWT-MOT was expended to ERP-OWT in which the overall OWT business will be integrated by a software package. The database architecture of this tool was developed using the principles of relational database. It was mentioned that such a tool will improve the decision making ability of stakeholders by routinely managing the vast amounts of data that is generated from OWT on a daily basis.

This work also showed that mathematical optimisation of OWT maintenance is complex to implement and chance of its practical usefulness is low. Instead, cost intensive areas of OWT maintenance were identified and the role of a maintenance decision model in making optimal maintenance decision was shown. The role of maintenance in improving availability and productivity in OWT was seen to directly depend on repair time and downtime, which needs to be reduced. Some strategies for doing these were also identified. The role of upgrade technology in improving availability and productivity of OWT was also highlighted and associated mathematical relationships were derived.

6.3. Summary

This work identified a need to design systems and tools that can support in OWT maintenance. This is important in face of the challenges faced by OWT and if the LCoE of OWT was to be economised. However the extent of components in OWT, and the complexity in which these components operate and fail, require that drawbacks of traditional failure analysis methods are addressed and new strategies are used meet the needs of OWT maintenance planners. The use of FMECA$^+$ framework, new method to calculate RPN value and development of a FMECA$^+$ based software package are works dedicated to meet the needs of OWT maintenance planners.

In view of the current challenges, WT operators largely use their personal judgements or statistical methods to plan maintenance. This has undermined the use of condition monitoring and SCADA data to detect failures. However strategies would need to be designed (like use of a knowledgebase developed to map WT component level failures and its root causes) to enable greater use condition monitoring and SCADA data. This is important if the financial benefits of Condition Based Maintenance were to be realised. A need for smart analytical techniques, as an alternative to using many inspection methods, to detect failure in WT components was also identified and one such method was demonstrated in this work. However there is a need for many more such methods if the cost of offshore based inspection was to be controlled. A scheme for planning CBM was shown in Chapter 3 that incorporates a module of self-learning prognostic system in which failures are analysed using intelligent systems, their occurrences noted and a knowledgebase updated. Such a knowledgebase will enable site specific prediction of failures. This will be beneficial for improving accuracy of failure detection however to validate this model, more specific OWT data is required.

6.4. Avenues for Future work

Some areas for future work are given below.

1) Power generated from V52 and V47 WT were seen to be maximised when the blades and the yaw system were inclined in the direction of incoming wind. However being mechanical systems, the time lost in alignment necessitates use of smart controllers that can move Yaw and Pitch systems in anticipation of wind direction/speed. Work is needed to develop such smart controllers.
2) In order to limit offshore visit for inspection purposes, online failure detection methods need to be developed to identify failures/faults in OWT components.
3) There is a need to develop knowledgebase that will control human fallacies and standardise maintenance activities.
4) There is also a need to include OWT maintenance under the purview of project management so that errors/complexities in planning are controlled.
5) Avenues should be identified in OWT maintenance that requires automation and so tools should be developed for the purpose.
6) An optimal inventory need to be planned for OWT in order to reduce instances delayed or deferred maintenance in the absence of spare part
7) A reliability database is required to be developed and populated by real failure and maintenance data.
8) OWT businesses needs to have policies that enable collaboration to further research work in OWT maintenance. It is only then that an accurate and viable result from optimisation work can be verified.

6.5. Final Conclusion

In Figure 1.2 a comparison of various LCoE for different power projects in the UK were given. It was seen that the LCoE of Gas, Coal, Nuclear, Offshore Wind, Onshore Wind, Biomass and Solar were in the order of £80/MWh, £100-

120/MWh, £80/MWh, £120-130/MWh, £90-110/MWh, £110-£130/MWh and £164/MWh respectively. However these prices have varied over time and place. For example, according to Narbel, Hansen, and Lien (2014, pg. 212), the LCoE for various technologies are as given in Figure 6.1. According to Figure 6.1, the median LCoE for OnWT and OWT are £66/MWh and £95.38/MWh respectively (£1 = 1.3 Euro). This shows that the LCoE for OnWT and OWT are decreasing.

Technology	Class	Median cost in Euro/MWh
Large hydropower	b	30
Near-surface geothermal	b	34
Black coal all	a	44
Black coal supercritical	a	45
Natural gas CCGT	a	53
Black coal with CC(S)	a	56
Natural gas all	a	55
Nuclear all	b	57
Solid biomass	c	61
Nuclear PWR	b	69
Wind onshore	c	86
Wind offshore	c	124
Small hydro	c	129
Solar CSP	c	165
Solar PV	c	232

Figure 6.1 Shows the LCoE, Capital Cost, Operation and Maintenance cost and fuel cost for various power systems (Source: Narbel, Hansen, and Lien, 2014) (£1 = 1.3 Euro)

The retail cost of electricity in the UK is in between £120 - £170/MWh as different vendors use a variety of power projects to their source electrical power. Due to renewable obligation, and with the decrease in LCoE for OWT and OnWT, it is expected that the retail cost of electricity in the UK may reduce in the future. However the LCoE of other power systems shown in Figure 6.1 indicate that much still need to be done if the LCoE of OnWT and OWT were to compete with more traditional technologies and the retail tariff was to reduce. Nuclear power stations offer non-intermittent power, have high safety records and offer lower LCoE than OWT and OnWT. This makes Nuclear power plants as a viable alternative to WT however, WT offer the feasibility of a distributed power system which has its own merits on generation, transmission and distribution of power. As a result, it is essential that the LCoE for OnWT and OWT are controlled.

The installed capacity of OnWT and OWT in the UK is shown in Figure 6.2. A total 13.3GW was generated due to this combined capacity in 2015. If the warranty period is considered as 5 years, and as maintenance of OWT is costlier than OnWT, it can be seen from Figure 6.2 that by 2020 significant financial expenditures will be incurred on OWT maintenance if the current maintenance schemes are not moderated. In addition, on an average 1.5GW of OWT capacity is proposed to be added each year for the next 5 years that will increase OWT capacity to over 10GW by 2020. If the cost of maintaining OWT by 2020 is determined using data of prevalent OWT maintenance schemes, £3billion/year will be incurred on maintenance of OWT by 2020 if current maintenance schemes were not changed.

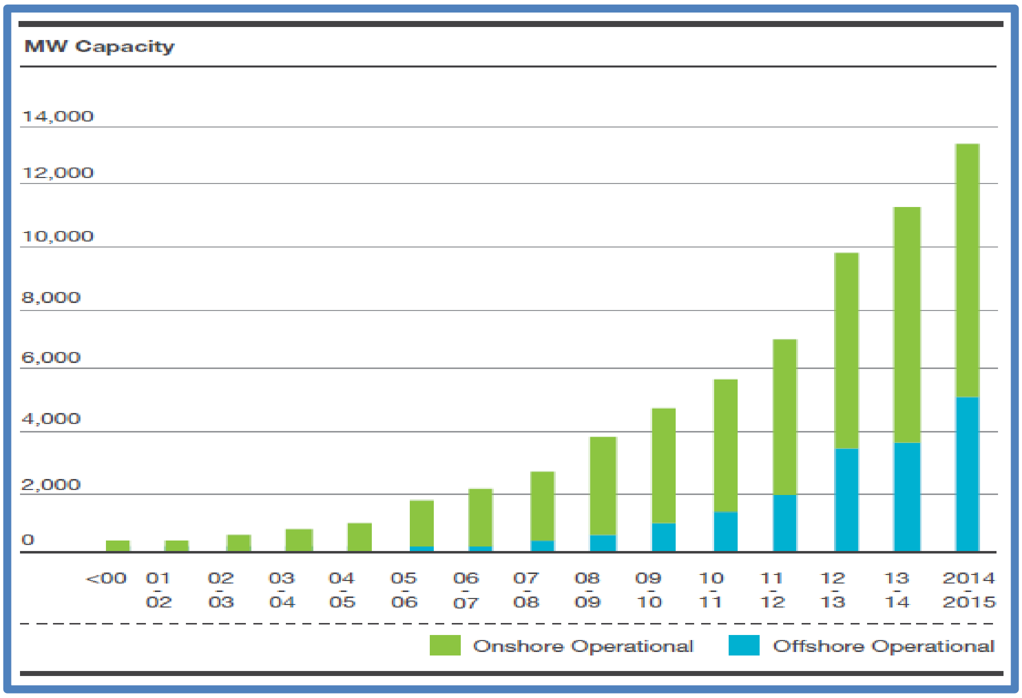


Figure 6.2 Shows operating capacity of OnWT and OWT in the UK[10]

[10] http://www.renewableuk.com/en/publications/reports.cfm/state-of-the-industry-report-2015 (Accessed: 12/03/2016)

Operators will need to be accustomed to their wind farm requirements and unless adequate preparations are done, such high recurring costs of OWT maintenance may prove detrimental for operators and service providers. Operators will need to use novel tools, new knowledge and adequate training, common sense and be proactive with the needs of their wind farms if their business was to be profitable and meet the aspirations of different stakeholders.

Many published works have debated on the benefits and deficiencies of using renewables in power systems. Policy makers often propose making use of fossil and nuclear based energy to meet the base demand of energy and recommend using renewables to meet the intermediate or peak demands of energy. However in a way they even propose the continual use of fossil and nuclear based energy systems despite their potential harms and limited supply. Although the above energy-mix scenario can meet the short term goals of reducing carbon emissions and controlling dependence on fossil fuels, there is a need to improve contribution level of renewables by ***supplying the necessary support mechanism*** on a continuous basis in order to gain the long term aim of a self-sustainable energy system. However if such necessary support mechanisms are not provided then there would be a need for a novel disruptive technology that can supply an inexhaustible amount of energy without causing harm to the environment or the ecology of mankind.

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APPENDIX

APPENDIX A. Abstracts of Published Papers

Journal	Wind Engineering
Publication	Volume 37, No. 6, 2013
Title of Paper	A SMART Software Package for Maintenance Optimisation of Offshore Wind Turbines
Authors	Yashwant Sinha, John A Steel, Jesse A Andrawus, Karen Gibson

Abstract

Offshore Wind Turbine (OWT) maintenance costs in between 20 – 35% of the lifetime power generation cost. Many techniques and tools that are being developed to curtail this cost are challenged by the stochastic climatic conditions of offshore location and the wind energy market. A generic and OWT centric software packages that can smartly adapt to the requirement of any offshore wind farm and optimise its maintenance, logistics and sparesholding while giving due consideration to offshore climate and market conditions will enable OWT operators to centralise their operation and maintenance planning and make significant cost reductions. This work aims to introduce the idea of a comprehensive tool that can meet the above objectives, and give examples of data and functions required. The package uses wind turbine condition monitoring data to anticipate component failure and proposes a time and maintenance implementation strategies that is developed as per the requirements of HSE and government regulations for working in the offshore locations and at heights. The software database contains key failure analysis data that will be an invaluable asset for future researchers, turbine manufacturers and operators that will optimise OWT power generation cost and better understand OWT working. The work also lists some prevalent tools and techniques developed by industries and researchers for the wind industry.

Journal	Wind Engineering
Publication	Volume 38(4), 2014
Title of Paper	Significance of Effective Lubrication in Mitigating System Failures – A Wind Turbine Gearbox Case Study
Authors	Yashwant Sinha, John A Steel, Jesse A Andrawus, Karen Gibson

Abstract

The effectiveness of lubrication in machines mainly depends on the physical and chemical properties of lubricating oil, like quantity, level of suspended particles, effect of external load / shear forces, temperature amongst others. Periodic inspection of lubricating oil for its grade of viscosity, H_2O content, fuel content, amount and nomenclature of suspended particles etc. assists maintenance personal in assessing the quality of oil and its residual life. Such assessments are also useful in determining health of the system in which the lubricating oil was used. This work discusses about industrial Wind Turbine Gearbox lubrication, its importance, applications, oil analysis method and lists constituents found in the oil. Results lead us to the conclusion that additives in the oil protect the gearbox from wear and tear during initial years of operation. Analysis also suggests that re-lubrication process should be performed every 18 month time interval to optimise the life of gearbox components. Other results and advice for lubrication are also listed.

Journal	Renewable and Sustainable Energy Reviews
Publication	Volume 42, 2015
Title of Paper	A progressive study into Offshore Wind Farm Maintenance Optimisation using Risk Based Failure Analysis
Authors	Yashwant Sinha, John A Steel

Abstract

Offshore Wind Farm consists of an array of Wind Turbines electrical, communication, command and control systems. At present the cost of maintaining Wind Turbines in the offshore locations is very high (about 35% of lifetime costs). This work puts emphasis on using failure analysis as a basis for designing a condition based prognostic maintenance plan in order to control cost of power and make maintenance more efficient. An essential aspect of such failure analysis is to identify wind turbine components, ascertain their failures and find root causes of the failures. However as a first step, identification of prominent failures in the critical assemblies of a wind turbine using available inspection methods and making provisions to control their occurrence would make significant contribution in improving wind turbine reliability. This work introduces Failure Modes Effects and Criticality Analysis (FMECA) as an important failure analysis tool that has in the past successfully benefitted the airlines, marine, nuclear and spacecraft industries. FMECA is a structured failure analysis technique that can also evaluate the risk and priority number of a failure and hence assist in prioritising maintenance works. The work shows, how with a slight modification of the existing FMECA method, a very useful failure analysis method can be developed for offshore wind turbines including its operational uniqueness. This work further proposes modifying the format for calculating the Risk Priority Number (RPN) for wind turbine failure. By using wind turbine gearbox as a case study, this work illustrates the usefulness of RPN number in identifying failures which can assist in designing cost effective maintenance plan. Some preliminary results of a FMECA tool that has been developed to automatically evaluate the effects and criticality of a failure in a wind turbine at the component level is included.

Journal	Wind Engineering
Publication	Volume 39(4), 2015
Title of Paper	Failure Prognostic schemes and database design of a software tool for efficient management of wind turbine maintenance
Authors	Yashwant Sinha, John A Steel

Abstract

Wind Turbines require numerous and varied types of maintenance activities throughout their lifespan, the frequency of which increases with years in operation. At present the proportion of maintenance cost to the total cost for wind turbines is significant particularly for offshore wind turbines (OWT) where this ratio is ~35%. If this ratio is to be reduced in-spite of adverse operating conditions, pre-mature component failures and absence of reliability database for wind turbine components, there is a need to design unconventional maintenance scheme preferably by including novel failure prediction methodologies. Several researchers have advocated the use of Artificial Neural Networks (ANN), Bayesian Network Theory (BNT) and other statistical methods to predict failure so as to plan efficient maintenance of wind turbines, however novelty and randomness of failures, nature and number of parameters involved in statistical calculations and absence of required amount of fundamental work required for such advanced analysis have continued to maintain the high cost of maintenance. This work builds upon the benefits of condition monitoring to design methods to predict generic failures in wind turbine components and exhibits how such prediction methods can assist in cutting the maintenance cost of wind turbines. This study proposes using a dedicated tool to assist with failure prediction and planning and execution of wind turbine maintenance. The design and development of such an all-inclusive tool will assist in performing administrative works, inventory control, financial calculations and service management apart from failure prediction in wind turbine components. Its database will contain reference to standard management practices, regulatory provisions, staff details and their skillsets, service call register, troubleshooting manuals, installation guide, service history, details of customers and clients etc. that would cater to multiple avenues of wind turbine maintenance. In order to build such a software package, a robust design of its database is crucial. This work lists prerequisites for choosing a physical database and identifies the benefits of relational database software in controlling large amounts of data of various formats that are stored in such physical databases. Such a database would be an invaluable resource for reliability studies, an area of interest for both academic researchers and the industry that are identifying avenues to economise wind turbine operations.

Journal	Wind Engineering
Publication	Accepted for publication in volume 39, issue 5
Title of Paper	A Prognostic Decision Model for Offshore Wind Turbines Maintenance
Authors	Yashwant Sinha, John A Steel

Abstract

Frequent unscheduled random maintenance activities have significantly increased the operating cost of Offshore Wind Turbines (OWT). These activities account for ~65% of the overall OWT maintenance costs or 23% of the lifetime costs of OWT, equivalent to ~ £26M/yr for a 100MW offshore wind farm. This work performs a quantitative evaluation of the maintenance model suggested by Sinha Y et al (2013) as a means to determine the threshold levels for planning an economical but effective maintenance for OWT. This study suggests that the model put forward indeed provides a comprehensive framework to make maintenance decisions for OWT components by questioning about their Availability, Reliability, Safety, Productivity and Availability of Upgrade Technology. Some case studies have been discussed towards the end of this work that validates this model and brings financial benefits. It is expected that practical use of the maintenance decision model, along with relationships developed in this work, would invariably result in planning for an economical, effective and efficient OWT maintenance.

APPENDIX B (i). Sample Inspection Report 1 (source: Stork Technical Services)

STORK Stork Optimization Services

Customer	:
Contact	:
Location	:
Reference no. customer	:
Reference no. Stork	:
Date of inspection	:
Date of report	:
Author/Inspector	:
Verified by	:
Distribution	:
	:

Contents

1 Introduction

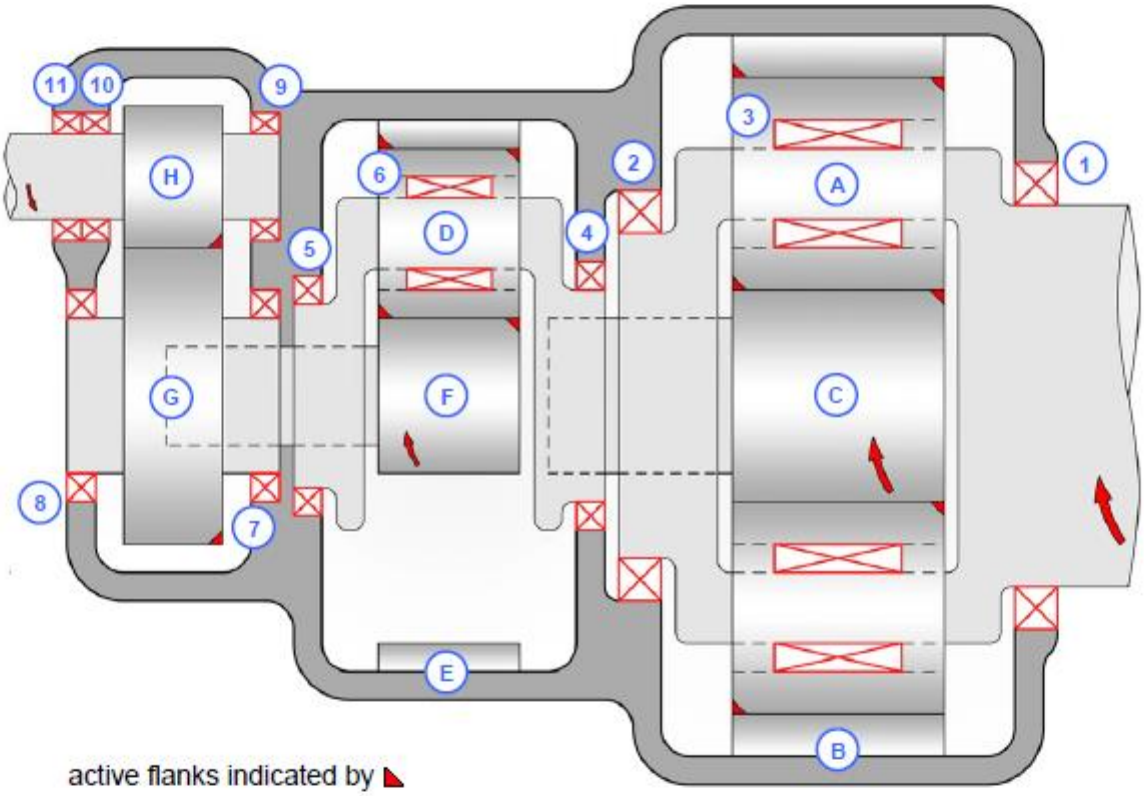
This report presents the results of the visual inspection, carried out on the gearbox of Wind Turbine

Stork Optimization Services was invited by to carry out the above-mentioned activities, to assess the condition of the gearbox. The gearbox inspection is part of an end-of-warranty inspection of the entire turbine, carried out by In order to visually inspect the planetary part of the gearbox, a videoscope, brand GE, type Everest XLG3, was used.

For the vibration measurement, a portable spectrum analyser, brand CSi, type 2130, was used. The acquired data has been stored and can be used as a reference for future measurements. We would like to emphasize that possible damage to the bearings of the planet gears is hard to detect by means of vibration measurement. The reason for this is the rotating movement of the planet gears relative to the ring gear, as well as the distance between the vibration sensor and the bearings.

2 Data and gearbox configuration

Gearbox manufacturer	: Eickhoff	Ratio	: i = 68.1762
Type	: CPNHZ-244	Input speed	: 16.78 rpm
Serial no	: 20294	Oil type	: Castrol Optigear Synthetic A 320
Power	: 2692 kW		
Torque	: 1532 kNm	Oil quantity	: 300 ℓ



Low speed planetary stage:
A = planet gears (4 units)
B = ring gear
C = sun gear

High speed planetary stage:
D = planet gears (3 units)
E = ring gear
F = sun gear

Parallel stage:
G = gear low speed shaft
H = pinion high speed shaft

Low speed planetary stage:
1 = bearing planet carrier, rotor side
2 = bearing planet carrier, generator side
3 = planet gear bearings

High speed planetary stage:
4 = bearing planet carrier, rotor side
5 = bearing planet carrier, generator side
6 = planet gear bearings

Parallel stage:
7 = bearing low speed shaft, rotor side
8 = bearing low speed shaft, generator side
9 = bearing high speed shaft, rotor side
10 = radial bearing high speed shaft, generator side
11 = axial bearing high speed shaft, generator side

3 Findings

3.1 *Visual Inspection*

As far as possible, all flanks and bearings inside the gearbox were inspected. Because of the arrangement of the gearbox, it was not possible to inspect all flanks of the ring gears, the planet gears and the sun gears. Also, the low speed stage planet carrier bearing, generator side (bearing 2), as well as the high speed stage planet carrier, rotor side (bearing 4), were inaccessible for inspection.

During the days before the inspection, the turbine was not running. Because of this, the gearbox was cold (ambient temperature 0°C), rendering the oil viscosity high. This made the following sections of the gearbox inaccessible without severely polluting the videoscope lens: both sun gears, the low speed planet carrier bearing, rotor side (bearing 1), as well as the high speed planet carrier bearing, generator side (bearing 5). Therefore, no clear pictures of these gears and bearings exist.

A telemetry system, installed at the shrink disk of the input shaft, complicated access to the low speed planetary part.

<u>Low speed planetary stage, planet carrier bearings</u>
- The bearing is completely filled with oil. From the pictures, no damage can be discerned. See picture 1.
- The generator side was not accessible for inspection.

<u>Low speed planetary stage, planet gears</u>
- On the ring gear-active flank, no significant damage has been found. See picture 2.
- On the sun gear-active flanks, no significant damage has been found. See picture 3.

<u>Low speed planetary stage, planet gear bearings</u>
- On the rolling elements, areas of micropitting have been observed. See pictures 4 and 5.

<u>Low speed planetary stage, ring gear</u>
- On the dedendum of the active flanks, interference wear has been observed. The amount of wear is not considered to be severe. See picture 6.
- On none of the inactive flanks, significant damage has been found. See picture 7.

<u>Low speed planetary stage, sun gear</u>
- On the active flanks, no damage can be discerned from the pictures. See picture 8.
- On the inactive flanks, no damage can be discerned from the pictures. See picture 9.

<u>High speed planetary stage, planet carrier bearings</u>
- The rotor side bearing was not accessible for inspection.
- From the pictures, no damage can be discerned. See picture 10.

High speed planetary stage, planet gears

- On the ring gear-active flanks, a fine scratch pattern has been observed. The situation is not considered to be severe See picture 11.
- The sun gear-active flanks do not show any significant damage. See picture 12.

High speed planetary stage, planet gear bearings

- None of the bearings show any wear or damage. See picture 13.

High speed planetary stage, ring gear

- On the dedendum of the active flanks, interference wear has been observed. The amount of wear is not considered to be severe. See picture 14.
- On the inactive flanks, standstill marks have been found. See picture 15.

High speed planetary stage, sun gear

- On the active flanks, no damage can be discerned from the pictures. See picture 16.
- On the inactive flanks, no damage can be discerned from the pictures. See picture 17.

Parallel stage, gear, low speed shaft

- None of the flanks of the gear show any wear or damage. Picture 18 shows the active flank.

Parallel stage, bearings, low speed shaft

- The rolling elements of the rotor side bearing show a dull appearance. This is most likely caused by foreign material, caught in the bearing. The situation is not expected to affect the functionality of the gearbox. See picture 19.
- As far as visible, the generator side bearing does not show any wear or damage. See picture 20.

Parallel stage, bearings, high speed shaft

- The rotor side bearing does not show any wear or damage. See picture 22.
- The generator side radial bearing does not show any wear or damage. See picture 23.
- As far as visible, the generator side axial bearing does not show any wear or damage. See picture 24.

Other findings

- By dragging a magnet across the bottom of the casing of the parallel part, a small amount of chips was found.
- Oil is above the required level.
- No significant oil leakages were found.

3.2 Vibration Measurement

<u>Load conditions during measurement</u>

Wind Speed	: 4.5 m/s
Power Generated	: 300 kW
Generator Speed	: 920 rpm

During the vibration measurement, the wind turbine was running at approximately 12% of its rated load. Gear and bearing damage patterns can more easily be detected when the gearbox load is higher.

The highest overall vibration level recorded at the generator is 1.75 mm/s RMS (10-1000 Hz). According to standard ISO 10816-3, this vibration level is acceptable.

The highest overall vibration level recorded at the gearbox is 0.65 mm/s RMS (10-1000 Hz). According to standard ISO 10816-3, this vibration level is acceptable.

No irregularities were observed in the spectra, recorded at the generator. As an example, the spectrum, recorded at the non-driven end, in vertical direction, is presented in figure 1.

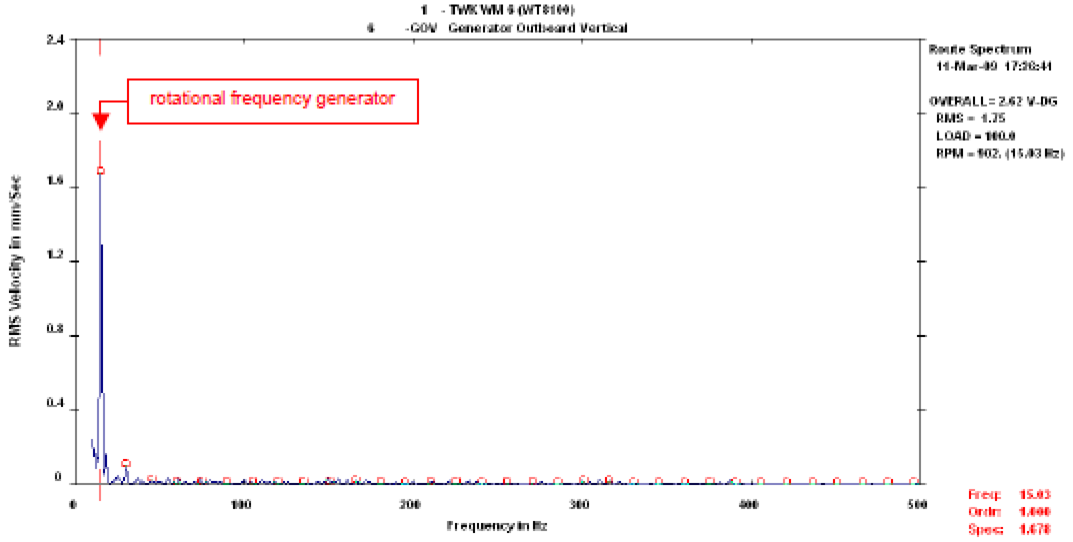


Figure 1: Spectrum at generator, non-driven end, vertical

No irregularities were observed in the spectra, recorded at the gearbox. Only rotational and gear mesh frequencies were observed. As an example, the spectrum, recorded at the high speed shaft bearing, generator side, in horizontal direction, is presented in figure 2.

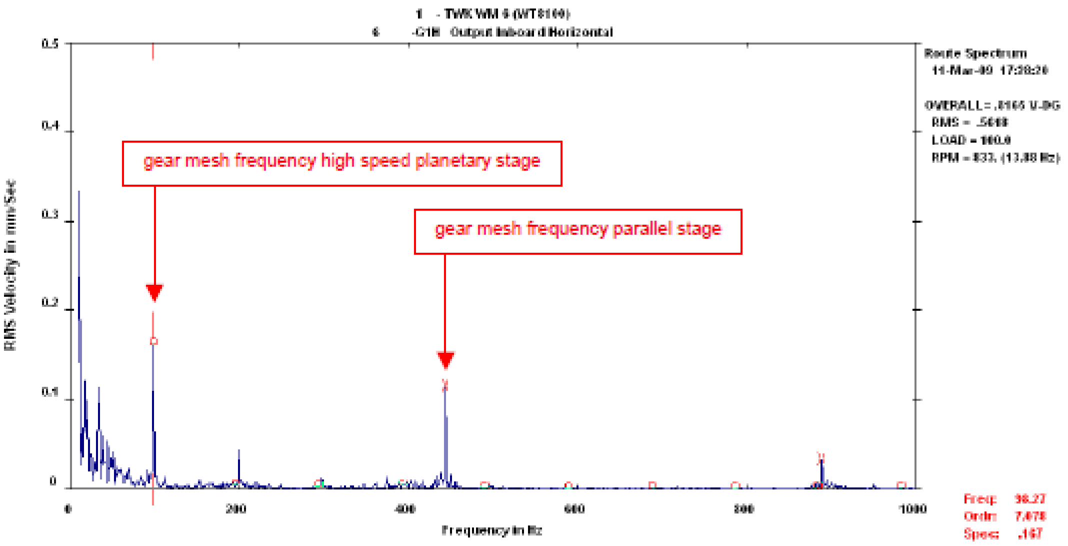


Figure 2: spectrum at high speed shaft, generator side, horizontal

3.3 *Oil Analysis*

The oil analysis indicates that:

- The oil is contaminated.
- The iron content is at an increased level.

After changing the filter element, the oil is suitable for further use.

A detailed analysis report is included in Appendix 2.

4 Conclusions

Because of the high oil viscosity (cold gearbox), some sections of the gearbox were not accessible for inspection without severely polluting the videoscope lens. Therefore, no clear pictures of these sections exist.

On the rolling elements of the low speed stage planet gear bearings, areas with micropitting have been observed. Micropitting is a form of surface fatigue, which may develop into larger scale flaking, eventually leading to bearing failure. Micropitting is caused by rough mating surfaces (in this case, possibly the rolling elements of the cageless bearing rubbing against each other), in combination with poor lubrication conditions.

All other observations can be classified as normal wear.

During the vibration measurement, no signs of gear or bearing damage were observed. However, it must be noted that the load conditions were not optimal for the detection of gear and bearing damage.

The oil analysis indicates contamination and increased iron content.

5 Recommendations

It is recommended to perform an inspection of the low speed stage planet gear bearings within 12 months, in order to determine the progression of the observed damage.

Furthermore, it is recommended to inspect the sections of the gearbox that were inaccessible during this inspection as soon as possible. To make this inspection possible, the gearbox must be warm (turbine running, to be stopped only shortly before inspection).

It is recommended to change the oil filter.

Appendix 1: Pictures

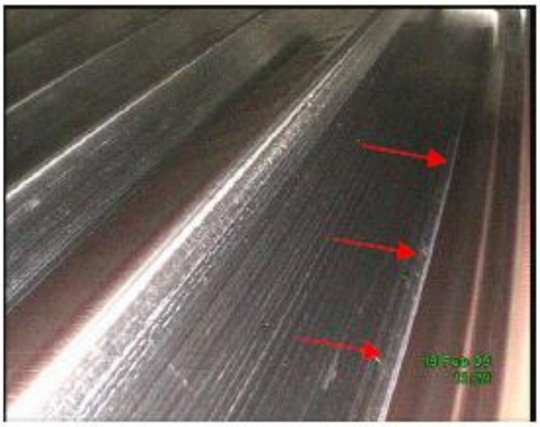
Picture 1: low speed planetary stage,
planet carrier bearing, rotor side

Picture 2: low speed planetary stage,
planet gear, ring gear-active flank

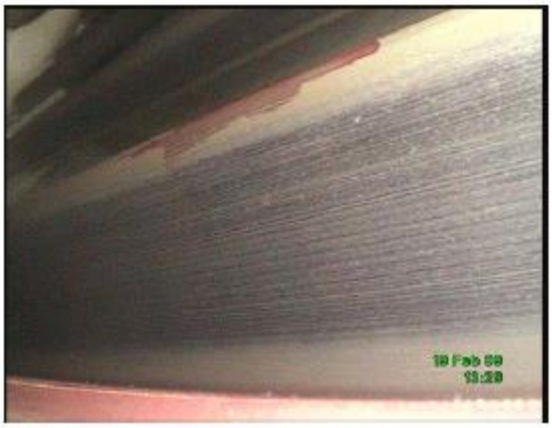
Picture 3: low speed planetary stage,
planet gear, sun gear-active flank

Picture 4: low speed planetary stage,
planet gear bearing

Picture 5: low speed planetary stage,
planet gear bearing



Picture 6: low speed planetary stage,
ring gear, active flank

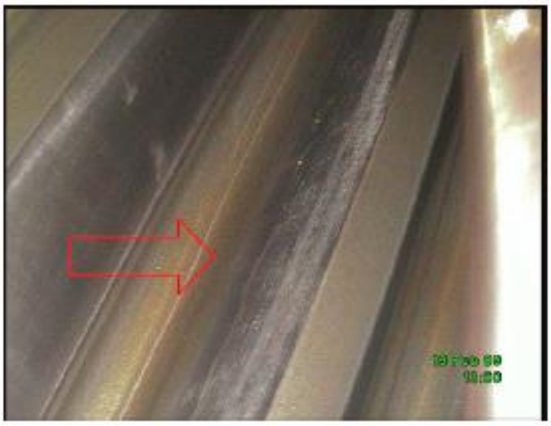


Picture 7: low speed planetary stage,
ring gear, inactive flank

Picture 8: low speed planetary stage,
sun gear, active flank

Picture 9: low speed planetary stage,
sun gear, inactive flank

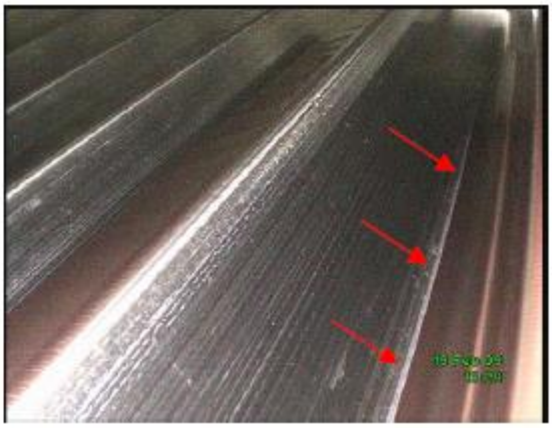
Picture 10: high speed planetary stage,
planet carrier bearing, generator side



Picture 11: high speed planetary stage,
planet gear, ring gear-active flank

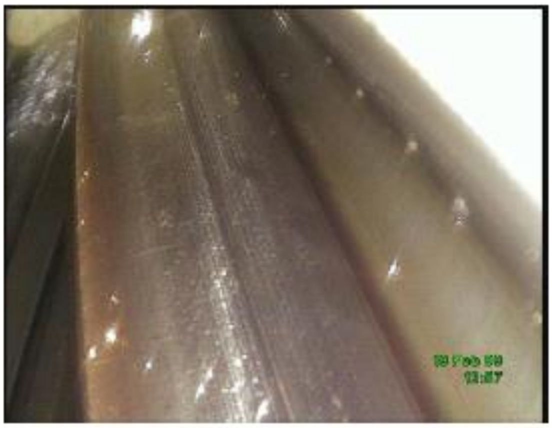
Picture 12: high speed planetary stage,
planet gear, sun gear-active flank

Picture 13: high speed planetary stage, planet gear bearing

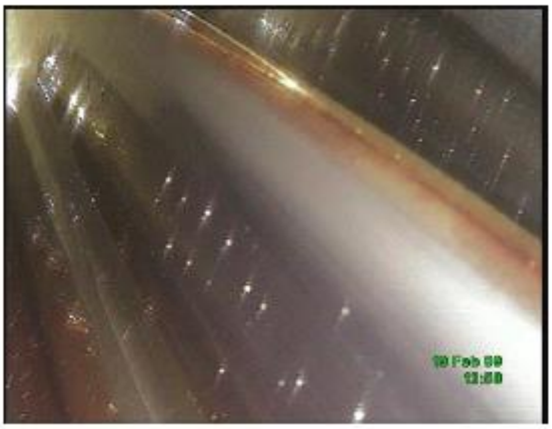


Picture 14: high speed planetary stage, ring gear, active flank

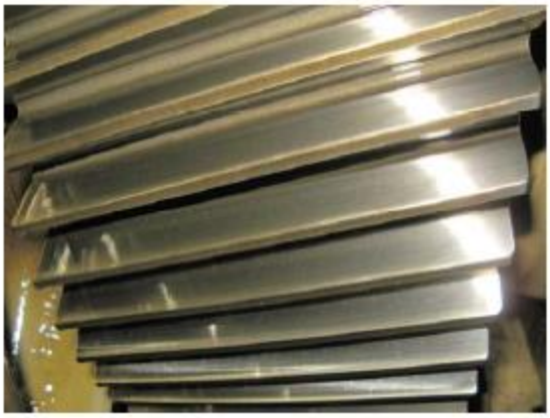
Picture 15: high speed planetary stage, ring gear, inactive flank



Picture 16: high speed planetary stage, sun gear, active flank



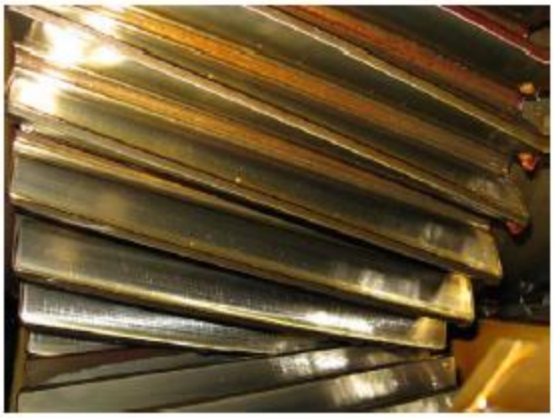
Picture 17: high speed planetary stage, sun gear, inactive flank



Picture 18: parallel stage, gear low speed shaft, active flank

Picture 19: parallel stage,
bearing low speed shaft, rotor side

Picture 20: parallel stage,
bearing low speed shaft, generator side



Picture 21: parallel stage,
pinion high speed shaft, active flank

Picture 22: parallel stage,
bearing high speed shaft, rotor side

Picture 23: parallel stage,
bearing high speed shaft, generator side
radial

Picture 24: parallel stage,
bearing high speed shaft, generator side
axial

Appendix 2: Oil Analysis

Date:		Engine model:	T6 ECN
Rapportnr:		Engine manufacturer	
Lab.nr.:		Operating hours:	
		Type of oil :	CASTROL OPTIGEAR A320
Customer:		Number of operating hours since last oil change:	
Sample Reference :		Sampling date :	
		Sampling location :	

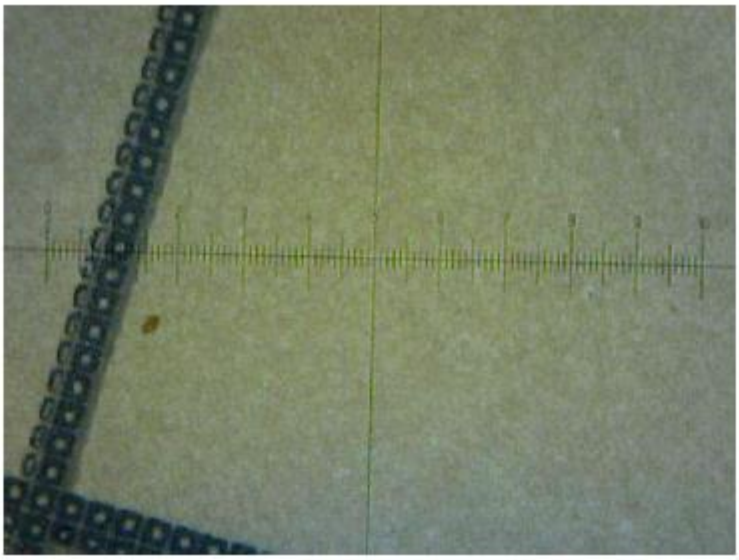
OIL IS CONTAMINATED, CONTAINS A LOT OF PARTICLES < 10 MICRON.
TAKE CARE OF IRON WEAR.ALUMINIUM AND MOLYBDEN ARE ADDITIVES.
CHEMICAL, THE OIL FALLS FURTHER WITHIN SPECIFICATIONS. AWAIT FOR NEXT SAMPLE.
THE OIL IS AFTER ELEMENTCHANGE OR BY-PASS FILTRATION SUITABLE FOR FURTHER USE.

Oil Condition

AR-nr.	Datum Sample	Hours		ISO	NAS	Visc 40°C	Visc 100°C	TAN	TBN	Fuel	Water ppm
AR0903362	11.03.09			20/13	11	302.70		3.07			140

	Additive Elements (ppm)							Wear Metals (ppm)							
AR-nr.	Na	B	Zn	P	Ca	Mg		Si	Fe	Cr	Mo	Al	Cu	Pb	Sn
AR0903362	12	0	990	961	36	1073		3	33	1	303	31	2	0	0

Normal	Caution	Serious



> 2	1221890
> 5	988700
> 10	75470
> 15	6640
> 25	890
> 50	115
> 75	40
> 100	10

APPENDIX B (ii). Sample Inspection Report 2 (source: Stork Technical Services)

STORK®

Stork Optimization Services

Customer
Contact
Location

Reference no. customer
Reference no. Stork

Date of inspection
Date of report

Author
Verified by
Distribution

Contents

1 Introduction

This report presents the results of the visual inspection, carried out at the gearbox of the GE1.5S wind turbine

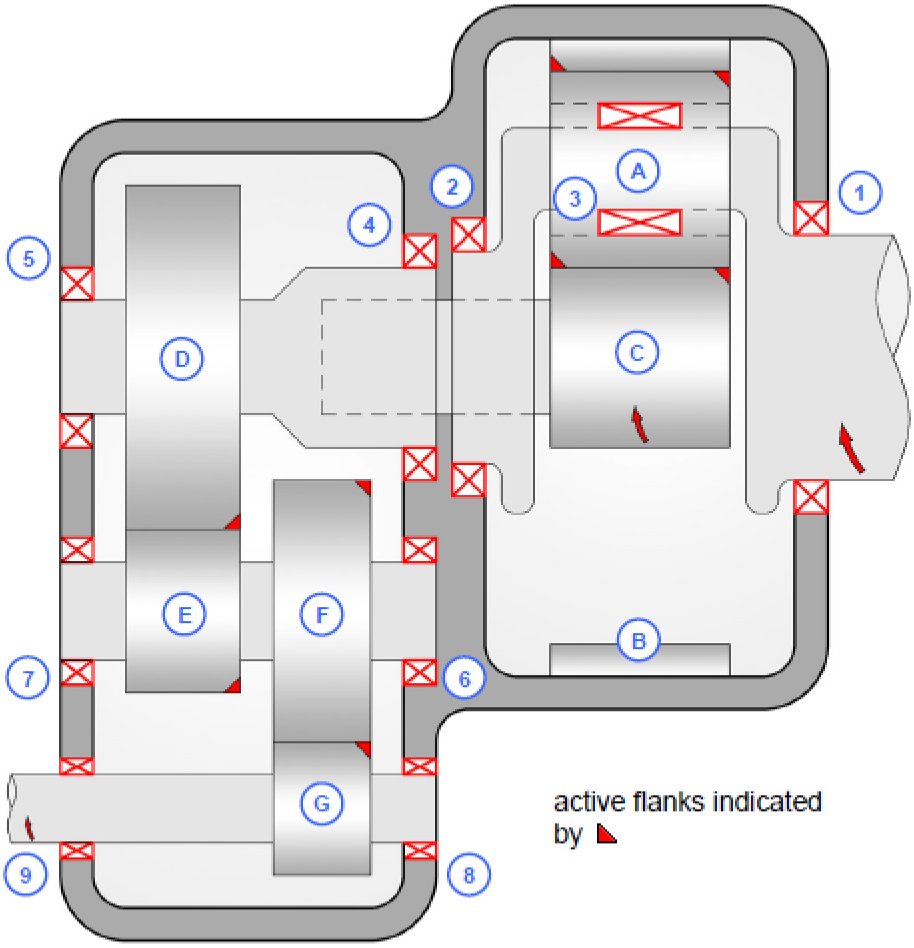
Stork Optimization Services was invited by Siemens to carry out the above-mentioned activities, in order to assess the condition of the gearbox. In order to visually inspect the planetary part of the gearbox, an endoscope, brand GE, type Everest XLG3, was used.

During the inspection, an oil sample has been taken from the gearbox. The analysis results of the sample are included in this report.

In case any questions arise regarding this report, please do not hesitate to contact us.

2 Gearbox data and configuration

Brand	: Lohmann + Stolterfoht	Ratio	: i = 88.81
Type	: GPV451	Input speed	: 20 rpm
Number	: 1048177	Weight	: 13,900 kg
Power	: 1,500 kW	Type of oil	: Castrol Optigear Synthetic A320 (380 liter)



active flanks indicated by

A = planet wheels (3 units)
B = ring gear
C = sun wheel
D = gear first intermediate shaft
E = pinion second intermediate shaft
F = gear second intermediate shaft
G = pinion output shaft

1 = bearing planet carrier, blade side
2 = bearing planet carrier, generator side
3 = planet wheel bearings
4 = bearing first intermediate shaft, blade side
5 = bearing first intermediate shaft, generator side
6 = bearing second intermediate shaft, blade side
7 = bearing second intermediate shaft, generator side
8 = bearing output shaft, blade side
9 = bearing output shaft, generator side

3 Findings

3.1 Visual inspection

As far as possible, all flanks and bearings inside the gearbox were inspected. Because of the arrangement of the gearbox, it was not possible to inspect all flanks of the ring gear, the planet wheels and the sun wheel. Also, the planet carrier bearing at generator side and the second intermediate shaft bearing at generator side were not accessible.

Planet carrier bearing
- The planet carrier bearing, blade side, showed no wear or damage, see picture 1 in appendix 1.

Planet wheels
- None of the planet wheel flanks showed significant damage, see pictures 2 to 4 in appendix 1.

Planet wheel bearings
- On the outer ring of one of the planet wheel bearings, a mark, caused by a piece of foreign material, was found. See picture 5 in appendix 1.
- None of the other planet wheel bearings showed wear or damage, see pictures 6 to 8 in appendix 1. However, the rolling elements of the planet wheel bearings showed a dull grey appearance (see picture 6 and 8).

Ring gear
- The active flanks of the ring gear showed no significant damage, see pictures 9 and 10 in appendix 1.
- The inactive flanks of the ring gear showed no significant damage.

Sun wheel
- The active flanks showed no significant damage, see pictures 11 and 12 in appendix 1.
- The inactive flanks showed no significant damage.

Gear, first intermediate shaft
- The active flanks showed no significant damage, see picture 13 in appendix 1.
- The inactive flanks showed no significant damage.

Bearings, first intermediate shaft
- As far as visible, the first intermediate shaft bearings showed no wear or damage, see pictures 14 and 15 in appendix 1.

Pinion, second intermediate shaft
- In the base of the active flanks micro pitting was observed, see picture 16 in appendix 1.
- The inactive flanks showed no significant damage.

Gear, second intermediate shaft
- The active flanks showed no significant damage, see picture 17 in appendix 1.
- The inactive flanks showed no signs of significant damage.

Bearings, second intermediate shaft

- As far as visible, the second intermediate shaft bearing at blade side showed no wear or damage. No clear picture of this bearing is available.
- The entire generator side bearing was located below the oil level.

Pinion, output shaft

- The active flanks of the pinion showed no significant damage, see picture 18.
- The inactive flanks of the pinion showed no significant damage.

Bearings, output shaft

- The output shaft bearings showed no wear or damage, see pictures 19 and 20.

Other findings

- Oil level at required level.
- No oil leakages found.

4 Conclusions

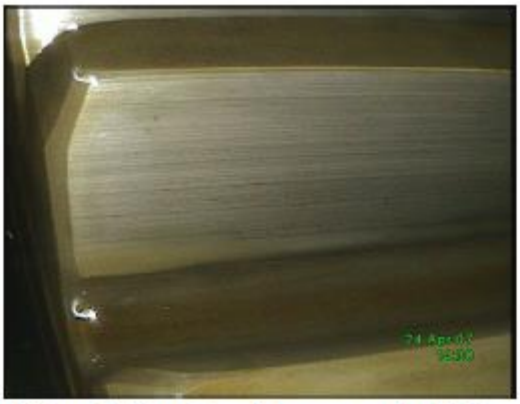
Minor damage (micro pitting) has been observed on the active flanks of the pinion on the second intermediate shaft. The progression of this damage may have stabilized, however, the damage might also develop into more severe pitting.

No other signs of bearing or gear damage were found during the visual inspection of the gearbox. However, the rolling elements of the planet wheel bearings showed a dull grey appearance, which is a sign of light abrasive wear.

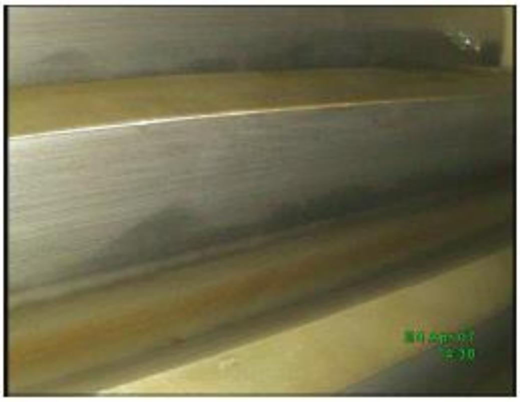
The oil in the gearbox is suitable for further use, see oil analysis in appendix 2.

Appendix 1: Pictures

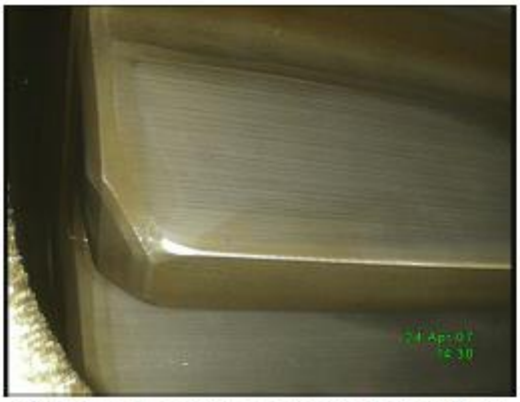
Picture 1: Planet carrier bearing, blade side



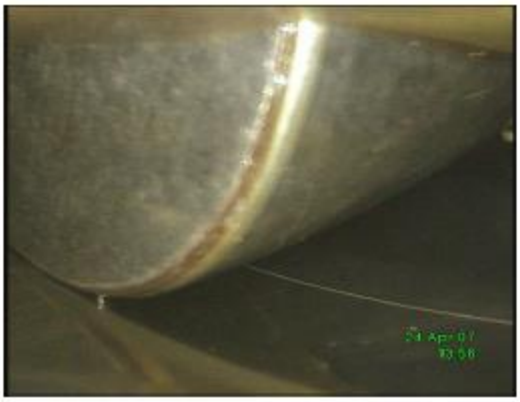
Picture 2: Planet wheel, ring gear-active flank



Picture 3: Planet wheel, ring gear-active flank



Picture 4: Planet wheel, sun wheel-active flank

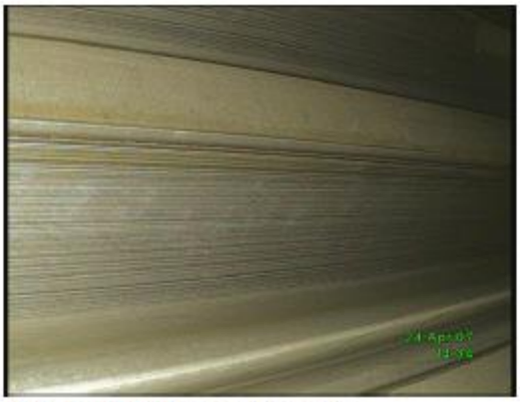


Picture 5: Bearing planet wheel

Picture 6: Bearing planet wheel

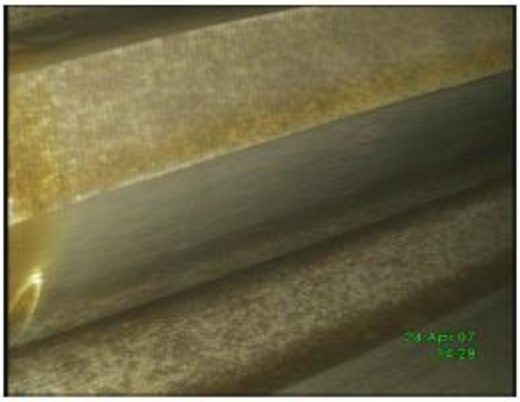
Picture 7: Bearing planet wheel

Picture 8: Bearing planet wheel

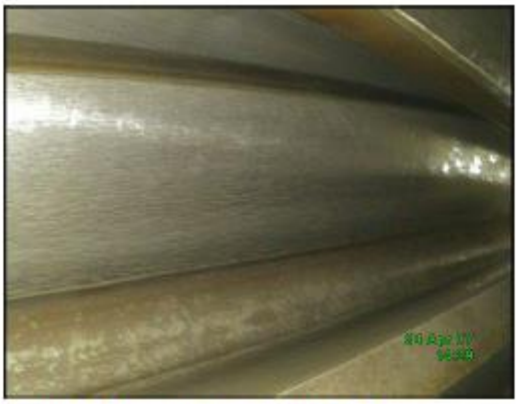


Picture 9: Ring gear, active flank

Picture 10: Ring gear, active flank



Picture 11: Sun wheel, active flank

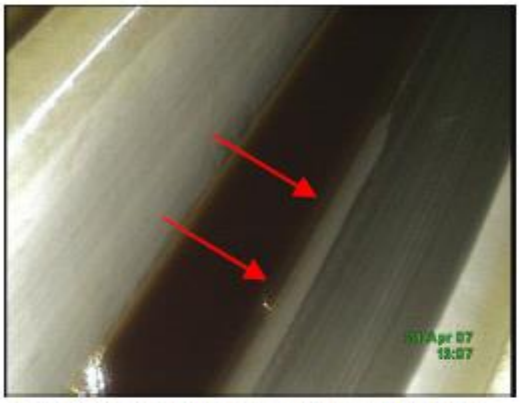


Picture 12: Sun wheel, active flank

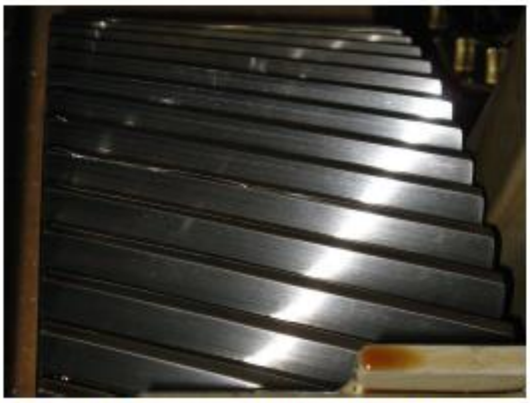
Picture 13: Gear first intermediate shaft, active flank

Picture 14: Bearing first intermediate shaft, blade side

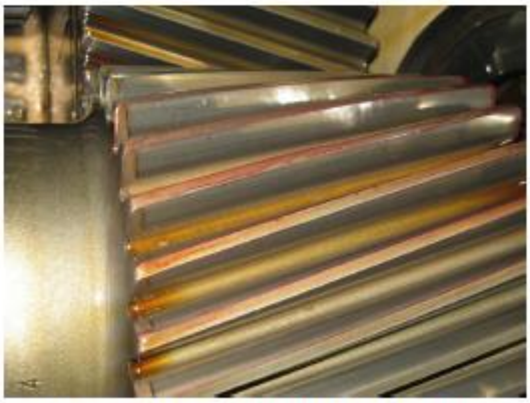
Picture 15: Bearing first intermediate shaft, generator side



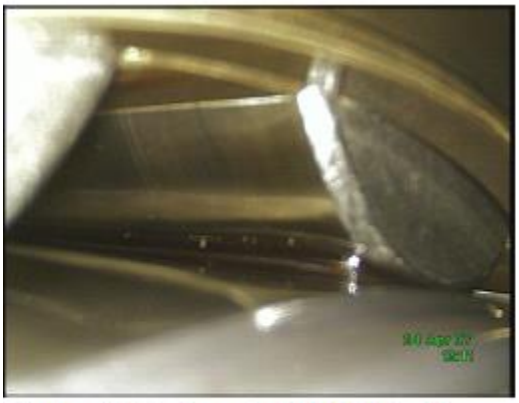
Picture 16: Pinion second intermediate shaft, active flank



Picture 17: Gear second intermediate shaft, active flank



Picture 18: Pinion output shaft, active flank



Picture 19: Bearing output shaft, blade side

Picture 20: Bearing output shaft, generator side

Appendix 2: Oil analysis

Oil analysis wind turbine

Oil type	:

Dates

Sample date
Arrival date lab
Analysis date
Oil change

Physical analysis

Density, kg/m^3	: 0.854
Viscosity 40ºC, cSt	: 328
Water, volume %	: <0.05
TAN	: 3

Element analysis

Iron (xfe)	:
Iron (fe)	: 10
Copper	: 20
Lead	: <1
Tin	: <1
Chrome	: <1
Nickel	: <1
Aluminum	: <10
Zinc	:
Silicium	: <10

Remark

The system is operating normal. The oil is suitable for further use.

APPENDIX C (i). Sample SCADA Data of V52 (source: Shetland Aerogenerators Ltd.)

Time Stamp	Turbine Availability Timer	Grid OK Timer	Grid ON Timer	Ambient OK Timer	Wind Speed OK Timer	Wind Speed Outside Nacelle (Avg) (m/s)	Wind Speed Outside Nacelle (Min) (m/s)	Wind Speed Outside Nacelle (Max) (m/s)	Wind Speed outside Nacelle SD (m/s)	Wind Direction Outside Nacelle (deg)
13/02/2013 04:40	600	600	600	600	600	13.2	9.4	16.2	1	164.2
13/02/2013 04:50	600	600	600	600	600	13.5	10.4	17.3	1.1	163.3
13/02/2013 05:00	600	600	600	600	600	13.5	10.4	16.6	1.1	158.4
13/02/2013 05:10	600	600	600	600	600	13.5	9.5	16.9	1.2	157
13/02/2013 05:20	600	600	600	600	600	13.1	10.1	16.7	1.1	161.7
13/02/2013 05:30	600	600	600	600	600	13.7	10.5	17.4	1.3	161.6
13/02/2013 05:40	600	600	600	600	600	12.3	9	15.3	1.1	163
13/02/2013 05:50	600	600	600	600	600	12.1	9.6	15.3	0.9	171.6
13/02/2013 06:00	600	600	600	600	600	12.5	8.9	15.6	1	169.4
13/02/2013 06:10	600	600	600	600	600	13.4	10.3	16.9	1.3	166.6
13/02/2013 06:20	600	600	600	600	600	13.4	9.2	18.4	1.5	167.7
13/02/2013 06:30	600	600	600	600	600	13.9	10.3	17.8	1.3	161.2
13/02/2013 06:40	600	600	600	600	600	14.1	10.2	18.1	1.5	154.1
13/02/2013 06:50	600	600	600	600	600	13.2	9.7	17.6	1.3	155.2
13/02/2013 07:00	600	600	600	600	600	13	9.1	16.7	1.1	153.3
13/02/2013 07:10	600	600	600	600	600	13.1	9.1	18.2	1.6	156.2
13/02/2013 07:20	600	600	600	600	600	15	10.1	19.1	1.8	166.1
13/02/2013 07:30	600	600	600	600	600	14.9	11.1	19.1	1.6	168.2
13/02/2013 07:40	600	600	600	600	600	15.8	10.6	19.5	1.7	160.5
13/02/2013 07:50	600	600	600	600	600	15.4	10.8	20.9	2	166.8
13/02/2013 08:00	600	600	600	600	600	15	9.2	20.6	2.1	163.9

Time Stamp	Total Operating Hours of Yaw	Nacelle Orientation (deg)	Nacelle Inclination (deg)	Temperature inside Nacelle (C)	Temperature Outside Nacelle (C)	Pitch Angle for Blade 1 (deg)	Pitch Angle for Blade 1 (deg)	Pitch Angle for Blade 1 (deg)	Pitch Angle for Blade 1 (deg)	Rotor Speed (RS) (rpm)
13/02/2013 04:40	15	168.3	355.9	9	4	5.6	-0.8	2.7	10.3	27
13/02/2013 04:50	30	161.1	2.1	9	4	7	0.9	2.1	11.7	26.9
13/02/2013 05:00	17	160.6	357.7	9	4	6.4	-0.4	2.5	10.8	26.9
13/02/2013 05:10	0	157.8	359.2	8	4	6.7	0.6	2.4	11.8	27
13/02/2013 05:20	0	157.8	3.9	8	4	6.1	-0.5	2.4	11.9	27
13/02/2013 05:30	13	159.1	2.4	8	4	6.9	-0.8	3.4	13.8	27
13/02/2013 05:40	43	159.7	3.2	9	4	3.4	-1.5	2.7	8.6	26.8
13/02/2013 05:50	0	167.9	3.7	9	4	2.3	-1.2	2.4	8	26.7
13/02/2013 06:00	0	167.9	1.5	8	4	3.7	-1.8	2.7	9.2	26.8
13/02/2013 06:10	0	167.9	358.7	8	4	6.2	-0.7	3	12.5	27
13/02/2013 06:20	0	167.9	359.8	8	3	6.4	-1.5	3.7	13.4	27.1
13/02/2013 06:30	18	165.7	355.5	7	3	7.6	-1.3	2.5	12.1	26.9
13/02/2013 06:40	16	157.2	356.9	7	2	8	-0.5	2.9	13.1	27
13/02/2013 06:50	0	153	2.2	7	2	6	-0.6	3.1	12.6	26.9
13/02/2013 07:00	0	153	0.3	8	3	5.3	-1.6	2.9	11.1	27
13/02/2013 07:10	14	153.1	3.1	8	3	5.4	-1.2	3.8	13.9	26.8
13/02/2013 07:20	12	162.1	4	8	4	10.2	-0.3	3.4	15.7	27
13/02/2013 07:30	12	165.6	2.5	8	4	10	2.2	2.9	15.3	27.6
13/02/2013 07:40	17	163.3	357.2	7	4	11.9	4.4	2.7	17.2	27.2
13/02/2013 07:50	13	165.2	1.5	7	4	11.1	1.8	3.5	18.5	27.5
13/02/2013 08:00	17	167.6	356.2	7	4	10.3	-0.5	3.8	18.4	27.4

Time Stamp	Rotor Speed (RS) (rpm)	Rotor Speed (RS) (rpm)	Rotor Speed (RS) (rpm)	Gearbox Oil Temperature (C)	Generator Operation Timer	Generator Stator Temperature (C)	Generator Speed (rpm)	Generator Slip Ring Temperature (C)	Generator Speed (rpm)	Generator Speed (rpm)
13/02/2013 04:40	25.6	0.1	26.1	57	600	105	1619	21	1679	1580
13/02/2013 04:50	25.7	0.1	26.1	56	600	105	1620	20	1663	1590
13/02/2013 05:00	25.5	0.2	26.1	55	600	104	1620	20	1670	1583
13/02/2013 05:10	25.6	0.1	26.1	55	600	103	1620	20	1668	1587
13/02/2013 05:20	25.6	0.1	26.1	54	600	103	1620	20	1668	1586
13/02/2013 05:30	25.5	0.1	26.1	56	600	102	1619	19	1671	1575
13/02/2013 05:40	25.5	0.2	26.1	57	600	101	1618	19	1663	1580
13/02/2013 05:50	25.5	0.2	26.1	58	600	101	1617	19	1657	1582
13/02/2013 06:00	25.4	0.2	26.1	58	600	101	1618	19	1666	1569
13/02/2013 06:10	25.7	0.2	26.1	57	600	101	1620	19	1673	1588
13/02/2013 06:20	25.6	0.2	26.1	56	600	100	1619	19	1678	1583
13/02/2013 06:30	25.2	0.2	26.1	55	600	100	1620	19	1670	1560
13/02/2013 06:40	25.4	0.2	26.1	55	600	100	1619	19	1672	1575
13/02/2013 06:50	25.5	0.2	26.1	54	600	100	1619	18	1671	1579
13/02/2013 07:00	25.4	0.2	26.1	55	600	100	1618	18	1668	1573
13/02/2013 07:10	25.2	0.2	26.1	56	600	99	1619	18	1664	1557
13/02/2013 07:20	25	0.2	26.1	58	600	99	1620	19	1676	1547
13/02/2013 07:30	25.5	0.2	26.1	58	600	100	1620	19	1702	1574
13/02/2013 07:40	25.2	0.2	26.1	58	600	100	1620	20	1681	1550
13/02/2013 07:50	25.3	0.3	26.1	57	600	100	1620	20	1707	1568
13/02/2013 08:00	25.2	0.2	26.1	56	600	100	1619	19	1699	1562

Time Stamp	Generator Speed (rpm)	Shaft Bearing Temperature (deg)	Operation Timer	GS Phase 1 (A)	GS Phase 2 (A)	GS Phase 3 (A)	GS Phase 1 (V)	GS Phase 2 (V)	GS Phase 3 (V)	Active Power (W)
13/02/2013 04:40	12	74	600	680.3	658.7	681.4	417	421.6	418.8	848400
13/02/2013 04:50	11	74	600	680.7	659.2	682.5	417.8	422	419	850200
13/02/2013 05:00	13	73	600	681	659.5	682.1	417.6	422	419	850000
13/02/2013 05:10	12	73	600	680.7	660.1	684	417.3	421.9	418.5	850300
13/02/2013 05:20	12	73	600	681.3	660.1	682.4	417.5	421.9	418.9	850200
13/02/2013 05:30	12	76	600	679.1	659.4	681.7	417.6	421.7	418.5	848600
13/02/2013 05:40	13	77	600	667.9	650.9	670.7	417.9	421.8	418.8	836100
13/02/2013 05:50	12	77	600	667.1	650.9	669.7	418.6	422.3	419.5	836600
13/02/2013 06:00	13	76	600	673.2	657	677.1	417.2	421	418	841900
13/02/2013 06:10	13	75	600	682.9	663.8	686	414.9	418.9	415.9	848300
13/02/2013 06:20	15	74	600	680	658.3	682	414.6	419	415.9	842700
13/02/2013 06:30	14	73	600	686.7	664.9	690.5	413.4	418.2	414.6	849600
13/02/2013 06:40	13	73	600	690.4	666.8	691.3	412.2	417	413.7	850300
13/02/2013 06:50	13	73	600	689.4	666.3	690.7	412.7	417.2	413.9	849900
13/02/2013 07:00	15	75	600	688.3	662.7	689	411.7	417.1	413.5	846200
13/02/2013 07:10	15	77	600	682.9	657.5	683.3	410.9	416.6	412.9	838200
13/02/2013 07:20	18	78	600	692.4	667.5	692.6	411.5	416.6	413	850400
13/02/2013 07:30	18	76	600	690.4	668.2	693.5	411.9	416.7	413	850400
13/02/2013 07:40	17	75	600	691.6	667.3	693.6	411.5	416.7	413	850400
13/02/2013 07:50	19	75	600	691.8	667.6	693.8	411.4	416.6	412.9	850500
13/02/2013 08:00	17	74	600	691.9	666.5	695.4	411	416.7	412.8	850300

Time Stamp	Active Power Generation Max (W)	Active Power Generation Min (W)	Active Power Generation SD (W)	Active Power Generation AVg (W)	Power Factor	Operating Frequency (Hz)	Controller Temperature (C)
13/02/2013 04:40	899800	745900	14000	848400	1	50.06	26
13/02/2013 04:50	861600	840300	3200	850200	1	50.08	26
13/02/2013 05:00	881200	808200	5400	850000	1	50.07	25
13/02/2013 05:10	863700	838100	3600	850300	1	50.06	25
13/02/2013 05:20	861900	839100	3600	850200	1	50.07	25
13/02/2013 05:30	864300	746100	10500	848600	1	50.06	27
13/02/2013 05:40	891300	627000	44000	836100	1	50.07	29
13/02/2013 05:50	897400	680900	35200	836600	1	50.1	29
13/02/2013 06:00	900200	656900	30200	841900	1	50.01	27
13/02/2013 06:10	892000	744900	13400	848300	1	49.9	26
13/02/2013 06:20	891000	636800	31200	842700	1	49.88	25
13/02/2013 06:30	894300	708100	11400	849600	1	49.85	25
13/02/2013 06:40	866200	828900	4600	850300	1	49.85	24
13/02/2013 06:50	875100	816100	6000	849900	1	49.87	24
13/02/2013 07:00	903200	644300	23900	846200	1	49.84	27
13/02/2013 07:10	896000	666200	36000	838200	1	49.82	28
13/02/2013 07:20	869400	835200	5200	850400	1	49.84	30
13/02/2013 07:30	866400	834800	4700	850400	1	49.85	28
13/02/2013 07:40	868800	832600	4700	850400	1	49.85	27
13/02/2013 07:50	875900	831500	5200	850500	1	49.85	27
13/02/2013 08:00	869400	819300	5000	850300	1	49.86	26

APPENDIX C (ii). Sample SCADA Data of V47 (source: Shetland Aerogenerators Ltd.)

Time Stamp	Turbine Availability Timer	Grid ON Timer	Grid OK Timer	Ambient OK Timer	Service Timer	Wind Speed OK Timer	Wind Speed Outside Nacelle (m/s)	Wind Speed Outside Nacelle (m/s)	Temperature inside Nacelle (C)	Temperature Outside Nacelle (C)
13/02/2013 03:20	600	600	600	600	0	600	13.4	16.5	21	7
13/02/2013 03:30	600	600	600	600	0	600	13.1	16.8	21	6
13/02/2013 03:40	600	600	600	600	0	600	14.2	17.2	21	6
13/02/2013 03:50	600	600	600	600	0	600	14.5	18.7	21	7
13/02/2013 04:00	600	600	600	600	0	600	14.2	18.3	22	7
13/02/2013 04:10	600	600	600	600	0	600	14.9	18	22	7
13/02/2013 04:20	600	600	600	600	0	600	13.7	16.9	21	7
13/02/2013 04:30	600	600	600	600	0	600	14.5	19.1	20	6
13/02/2013 04:40	600	600	600	600	0	600	13.4	16.7	20	6
13/02/2013 04:50	600	600	600	600	0	600	13.5	16.7	20	6
13/02/2013 05:00	600	600	600	600	0	600	13.9	17.9	20	6
13/02/2013 05:10	600	600	600	600	0	600	14.3	18.9	20	6
13/02/2013 05:20	600	600	600	600	0	600	15.6	18.8	21	6
13/02/2013 05:30	600	600	600	600	0	600	14.5	18.2	21	6
13/02/2013 05:40	600	600	600	600	0	600	15	19.1	21	6
13/02/2013 05:50	600	600	600	600	0	600	13.8	18	21	6
13/02/2013 06:00	600	600	600	600	0	600	13.7	17.7	21	6
13/02/2013 06:10	600	600	600	600	0	600	12.8	18.7	21	7
13/02/2013 06:20	600	600	600	600	0	600	17.2	20.9	22	7
13/02/2013 06:30	600	600	600	600	0	600	16.5	20.8	22	7
13/02/2013 06:40	600	600	600	600	0	600	16.4	20.1	22	7
13/02/2013 06:50	600	600	600	600	0	600	17	20.8	22	7

Time Stamp	Total Operating Hours of Yaw	Blade 1 Pitch Angle (Deg)	Rotor Speed RS (rpm)	Gearbox Oil Temperature (C)	Generator Operation Timer	Generator Stator Temperature (C)	Generator Speed (rpm)	Generator Speed (rpm)	Generator Slip Ring Temperature (C)	Shaft Bearing 1 Temperature (C)
13/02/2013 03:20	20	6.2	29.5	56	600	112	1561	1536	NaN	68
13/02/2013 03:30	10	6.7	29.5	57	600	113	1560	1522	NaN	68
13/02/2013 03:40	10	9.6	29.5	58	600	113	1562	1525	NaN	68
13/02/2013 03:50	10	10.1	29.5	58	600	113	1563	1523	NaN	69
13/02/2013 04:00	30	8.8	29.6	59	600	114	1563	1519	NaN	69
13/02/2013 04:10	0	10.7	29.5	59	600	114	1562	1522	NaN	69
13/02/2013 04:20	0	8.3	29.5	58	600	114	1562	1527	NaN	69
13/02/2013 04:30	0	9.4	29.6	57	600	114	1563	1526	NaN	69
13/02/2013 04:40	20	7.2	29.5	56	600	115	1562	1532	NaN	68
13/02/2013 04:50	0	6.8	29.5	56	600	115	1562	1526	NaN	67
13/02/2013 05:00	0	7.7	29.6	55	600	115	1563	1529	NaN	67
13/02/2013 05:10	0	10	29.5	54	600	115	1558	1515	NaN	67
13/02/2013 05:20	10	12	29.4	55	600	115	1557	1523	NaN	67
13/02/2013 05:30	20	9.7	29.4	56	600	115	1557	1513	NaN	67
13/02/2013 05:40	30	11.2	29.4	57	600	115	1555	1516	NaN	68
13/02/2013 05:50	0	8.8	29.4	57	600	116	1556	1513	NaN	68
13/02/2013 06:00	20	8.4	29.4	58	600	116	1556	1520	NaN	68
13/02/2013 06:10	0	5.9	29.4	58	600	116	1553	1513	NaN	69
13/02/2013 06:20	10	13.7	29.4	59	600	116	1556	1512	NaN	69
13/02/2013 06:30	10	13.1	29.4	58	600	116	1556	1514	NaN	69
13/02/2013 06:40	30	12.9	29.4	59	600	117	1557	1518	NaN	69
13/02/2013 06:50	60	14	29.4	59	600	117	1556	1513	NaN	69

Time Stamp	GS Phase 1 (A)	GS Phase 2 (A)	GS Phase 3 (A)	GS Phase 1 (V)	GS Phase 2 (V)	GS Phase 3 (V)	Total Power (W)	Active Power Generation (W)	Total Reactive Power (W)	Total Active Power (W)
13/02/2013 03:20	530	528.4	553.5	408.7	413.9	411	0	659900	-17776	109991
13/02/2013 03:30	529.7	525.6	552	409.5	413.1	411.7	0	658400	-17685	109734
13/02/2013 03:40	530.4	527.7	549.2	410.4	414.3	410.9	0	659900	-17768	109992
13/02/2013 03:50	528.2	527.6	550.2	410.9	415.3	411.6	0	659800	-17571	109972
13/02/2013 04:00	529.1	527.4	549	411.3	415.8	412.2	0	659800	-17648	109976
13/02/2013 04:10	527.8	528.6	551.2	409.8	415.4	411.8	0	659900	-17616	109978
13/02/2013 04:20	526.4	529.1	550.5	409	415	412.1	0	659700	-17808	109943
13/02/2013 04:30	527	527.9	551	409.2	415.2	412.8	0	659800	-17848	109976
13/02/2013 04:40	526.6	530.2	550.9	410	414.2	412.7	0	659800	-17886	109970
13/02/2013 04:50	526.1	527.7	547.7	411.4	414.1	413.4	0	659000	-17755	109827
13/02/2013 05:00	527.2	530.2	546.4	411.9	415.3	411.9	0	660000	-17874	110011
13/02/2013 05:10	531.4	533.2	554.1	407.7	411.7	409.5	0	659900	-18286	109978
13/02/2013 05:20	531.9	532.2	555.6	407.2	411.5	409.5	0	659900	-18186	109978
13/02/2013 05:30	531.8	531.6	556.6	407	411.7	409.1	0	659800	-18214	109968
13/02/2013 05:40	536	534.2	560.2	405.2	409.1	406.4	0	659800	-18512	109976
13/02/2013 05:50	535	534.1	558.5	404.8	410	407.7	0	659900	-18395	109978
13/02/2013 06:00	535.7	532.8	559.6	405.1	410	407	0	659800	-18376	109974
13/02/2013 06:10	533.1	532.6	560.1	402.9	409.5	406.6	0	657700	-18366	109613
13/02/2013 06:20	535.9	534.5	561.7	403.3	409.3	407	0	659900	-18481	109978
13/02/2013 06:30	536.4	534.8	560.5	404.7	408.9	406.1	0	659800	-18471	109977
13/02/2013 06:40	534.4	535.7	561.6	403.4	409.3	406.8	0	659900	-18495	109984
13/02/2013 06:50	537.1	534.7	560.7	404.6	408.9	405.9	0	659900	-18550	109980

Time Stamp	Total Reactive Energy (J)	Active Power Generation (W)	Power Factor	Operating Frequency (Hz)	Controller Temperature (C)
13/02/2013 03:20	-17776	659900	0.99	50.02	31
13/02/2013 03:30	-17685	658400	0.99	50.03	31
13/02/2013 03:40	-17768	659900	0.99	50.06	31
13/02/2013 03:50	-17571	659800	0.99	50.08	31
13/02/2013 04:00	-17648	659800	0.99	50.08	31
13/02/2013 04:10	-17616	659900	0.99	50.06	31
13/02/2013 04:20	-17808	659700	0.99	50.07	31
13/02/2013 04:30	-17848	659800	0.99	50.08	31
13/02/2013 04:40	-17886	659800	0.99	50.07	31
13/02/2013 04:50	-17755	659000	0.99	50.1	31
13/02/2013 05:00	-17874	660000	0.99	50.08	31
13/02/2013 05:10	-18286	659900	0.99	49.92	31
13/02/2013 05:20	-18186	659900	0.99	49.89	31
13/02/2013 05:30	-18214	659800	0.99	49.89	32
13/02/2013 05:40	-18512	659800	0.99	49.84	32
13/02/2013 05:50	-18395	659900	0.99	49.87	32
13/02/2013 06:00	-18376	659800	0.99	49.87	32
13/02/2013 06:10	-18366	657700	0.99	49.82	32
13/02/2013 06:20	-18481	659900	0.99	49.84	32
13/02/2013 06:30	-18471	659800	0.99	49.86	32
13/02/2013 06:40	-18495	659900	0.99	49.85	32
13/02/2013 06:50	-18550	659900	0.99	49.85	32

APPENDIX D. Sample list of Wind Turbine Components & their Codes

This Appendix lists a sample of the Wind Turbine components as provided by EU FP7 ReliaWind Consortium for reference proposes to highlight the process in which they can be provided a unique code in a wind farm. These can also be used to map components to their failures and maintenance schemes. As an example, 24GECH**F144** is a proposed code that designates failure number 144 in the Hose of a Cooling System in a Gearbox (Code: GECH) (No. 9 in the table given below). This code also denotes that the hose can be found in wind turbine number 24. The failure code 24GECH**F144** is mapped to the maintenance strategy code 24GECH**M144** in the database.

No.	System	Sub System	Assembly	Sub Assembly	Component	Code	Failure Code	Maintenance Code
1	Wind Turbine	-	-	-	-	WT	WTFXXXX	WTMXXXX
2	WT	Drive Train Module	-	-	-	DT	DTFXXX	DTMXXX
3	WT	Drive Train Module	Gearbox	-	-	GE	GEFXXX	GEMXXX
4	WT	Drive Train Module	Gearbox	Bearing	-	GEB	GEBFXXX	GEBMXXX
5	WT	Drive Train Module	Gearbox	Bearing	Carrier Bearing	GEBC	GEBCFXXX	GEBCMXXX
6	WT	Drive Train Module	Gearbox	Bearing	Planet Bearing	GEBP	GEBPFXXX	GEBPMXXX
7	WT	Drive Train Module	Gearbox	Bearing	Shaft Bearing	GEBS	GEBSFXXX	GEBSMXXX
8	WT	Drive Train Module	Gearbox	Cooling System	-	GEC	GECFXXX	GECMXXX
9	WT	Drive Train Module	Gearbox	Cooling System	Hose	GECH	GECHFXXX	GECHMXXX
10	WT	Drive Train Module	Gearbox	Cooling System	Pump	GECP	GECPFXXX	GECPMXXX
11	WT	Drive Train Module	Gearbox	Cooling System	Radiator	GECR	GECRFXXX	GECRMXXX
12	WT	Drive Train Module	Gearbox	Gears	-	GEE	GEEFXXX	GEEMXXX
13	WT	Drive Train Module	Gearbox	Gears	Hollow Shaft	GEEH	GEEHFXXX	GEEHMXXX
14	WT	Drive Train Module	Gearbox	Gears	Planet Carrier	GEEP	GEEPFXXX	GEEPMXXX
15	WT	Drive Train Module	Gearbox	Gears	Planet Gear	GEEX	GEEXFXXX	GEEXMXXX
16	WT	Drive Train Module	Gearbox	Gears	Ring Gear	GEER	GEERFXXX	GEERMXXX
17	WT	Drive Train Module	Gearbox	Gears	Spur Gear	GEES	GEESFXXX	GEESMXXX
18	WT	Drive Train Module	Gearbox	Gears	Sun Gear	GEEG	GEEGFXXX	GEEGMXXX
19	WT	Drive Train Module	Gearbox	Housing	-	GEH	GEHFXXX	GEHMXXX
20	WT	Drive Train Module	Gearbox	Housing	Bushing	GEHB	GEHBFXXX	GEHBMXXX

21	WT	Drive Train Module	Gearbox	Housing	Case	GEHC	GEHCFXXX	GEHCMXXX
22	WT	Drive Train Module	Gearbox	Housing	Mounting	GEHM	GEHMFXXX	GEHMMXXX
23	WT	Drive Train Module	Gearbox	Housing	Torque Arm System	GEHT	GEHTFXXX	GEHTMXXX
24	WT	Drive Train Module	Gearbox	Lubrication System	-	GEL	GELFXXX	GELMXXX
25	WT	Drive Train Module	Gearbox	Lubrication System	Hose	GELH	GELHFXXX	GELHMXXX
26	WT	Drive Train Module	Gearbox	Lubrication System	Motor	GELM	GELMFXXX	GELMMXXX
27	WT	Drive Train Module	Gearbox	Lubrication System	primary Filter	GELP	GELPFXXX	GELPMXXX
28	WT	Drive Train Module	Gearbox	Lubrication System	Pump	GELX	GELXFXXX	GELXMXXX
29	WT	Drive Train Module	Gearbox	Lubrication System	Reservoir	GELR	GELRFXXX	GELRMXXX
30	WT	Drive Train Module	Gearbox	Lubrication System	Seal	GELS	GELSFXXX	GELSMXXX
31	WT	Drive Train Module	Gearbox	Lubrication System	Secondary Filter	GELF	GELFFXXX	GELFMXXX
32	WT	Drive Train Module	Gearbox	Sensors	-	GES	GESFXXX	GESMXXX
33	WT	Drive Train Module	Gearbox	Sensors	Debris	GESD	GESDFXXX	GESDMXXX
34	WT	Drive Train Module	Gearbox	Sensors	Oil Level	GESO	GESOFXXX	GESOMXXX
35	WT	Drive Train Module	Gearbox	Sensors	Pressure 1	GESP	GESPFXXX	GESPMXXX
36	WT	Drive Train Module	Gearbox	Sensors	Temperature	GEST	GESTFXXX	GESTMXXX
37	WT	Drive Train Module	Generator	-	-	GN	GNFXXX	GNMXXX
38	WT	Drive Train Module	Generator	Cooling System	-	GNC	GNCFXXX	GNCMXXX
39	WT	Drive Train Module	Generator	Cooling System	Cooling Fan	GNCC	GNCCFXXX	GNCCMXXX
40	WT	Drive Train Module	Generator	Cooling System	Filter	GNCF	GNCFFXXX	GNCFMXXX
41	WT	Drive Train Module	Generator	Cooling System	Hose	GNCH	GNCHFXXX	GNCHMXXX
42	WT	Drive Train Module	Generator	Cooling System	Radiator	GNCR	GNCRFXXX	GNCRMXXX
43	WT	Drive Train Module	Generator	Lubrication System	-	GNL	GNLFXXX	GNLMXXX
44	WT	Drive Train Module	Generator	Lubrication System	Pump	GNLP	GNLPFXXX	GNLPMXXX
45	WT	Drive Train Module	Generator	Lubrication System	Reservoir	GNLR	GNLRFXXX	GNLRMXXX
46	WT	Drive Train Module	Generator	Rotor	-	GNR	GNRFXXX	GNRMXXX
47	WT	Drive Train Module	Generator	Rotor	Commutator	GNRC	GNRCFXXX	GNRCMXXX
48	WT	Drive Train Module	Generator	Rotor	Exciter	GNRE	GNREFXXX	GNREMXXX
49	WT	Drive Train Module	Generator	Rotor	Resistance Controller	GNRR	GNRRFXXX	GNRRMXXX
50	WT	Drive Train Module	Generator	Rotor	Rotor Lamination	GNRX	GNRXFXXX	GNRXMXXX
51	WT	Drive Train Module	Generator	Rotor	Rotor Winding	GNRY	GNRYFXXX	GNRYMXXX
52	WT	Drive Train Module	Generator	Rotor	Slip Ring	GNRS	GNRSFXXX	GNRSMXXX
53	WT	Drive Train Module	Generator	Sensors	-	GNS	GNSFXXX	GNSMXXX
54	WT	Drive Train Module	Generator	Sensors	Core Temperature Sensor	GNST	GNSTFXXX	GNSTMXXX
55	WT	Drive Train Module	Generator	Sensors	Encoder	GNSE	GNSEFXXX	GNSEMXXX
56	WT	Drive Train Module	Generator	Sensors	Wattmeter	GNSW	GNSWFXXX	GNSWMXXX

57	WT	Drive Train Module	Generator	Stator	-	GNT	GNTFXXX	GNTMXXX
58	WT	Drive Train Module	Generator	Stator	Magnet	GNTM	GNTMFXXX	GNTMMXXX
59	WT	Drive Train Module	Generator	Stator	Stator Lamination	GNTS	GNTSFXXX	GNTSMXXX
60	WT	Drive Train Module	Generator	Stator	Stator Winding	GNTW	GNTWFXXX	GNTWMXXX
61	WT	Drive Train Module	Generator	Structural & Mechanical	-	GNM	GNMFXXX	GNMMXXX
62	WT	Drive Train Module	Generator	Structural & Mechanical	Front Bearing	GNMF	GNMFFXXX	GNMFMXXX
63	WT	Drive Train Module	Generator	Structural & Mechanical	Housing	GNMH	GNMHFXXX	GNMHMXXX
64	WT	Drive Train Module	Generator	Structural & Mechanical	Rear Bearing	GNMR	GNMRFXXX	GNMRMXXX
65	WT	Drive Train Module	Generator	Structural & Mechanical	Shaft Bearing	GNMS	GNMSFXXX	GNMSMXXX
66	WT	Drive Train Module	Generator	Structural & Mechanical	Silent Block	GNMB	GNMBFXXX	GNMBMXXX
67	WT	Drive Train Module	Main Shaft Set	-	-	MT	MTFXXX	MTMXXX
68	WT	Drive Train Module	Main Shaft Set	High Speed Side	-	MTH	MTHFXXX	MTHMXXX
69	WT	Drive Train Module	Main Shaft Set	High Speed Side	Coupling	MTHC	MTHCFXXX	MTHCMXXX
70	WT	Drive Train Module	Main Shaft Set	High Speed Side	Rotor Lock	MTHR	MTHRFXXX	MTHRMXXX
71	WT	Drive Train Module	Main Shaft Set	High Speed Side	Shaft	MTHS	MTHSFXXX	MTHSMXXX
72	WT	Drive Train Module	Main Shaft Set	High Speed Side	Transmission Shaft	MTHT	MTHTFXXX	MTHTMXXX
73	WT	Drive Train Module	Main Shaft Set	Low Speed Side	-	MTL	MTLFXXX	MTLMXXX
74	WT	Drive Train Module	Main Shaft Set	Low Speed Side	Axial Bearing	MTLA	MTLAFXXX	MTLAMXXX
75	WT	Drive Train Module	Main Shaft Set	Low Speed Side	Compression Coupling	MTLC	MTLCFXXX	MTLCMXXX
76	WT	Drive Train Module	Main Shaft Set	Low Speed Side	Connector Plate	MTLP	MTLPFXXX	MTLPMXXX
77	WT	Drive Train Module	Main Shaft Set	Low Speed Side	Main Bearing Seal	MTLM	MTLMFXXX	MTLMMXXX
78	WT	Drive Train Module	Main Shaft Set	Low Speed Side	Main Bearing Temperature Sensor	MTLT	MTLTFXXX	MTLTMXXX
79	WT	Drive Train Module	Main Shaft Set	Low Speed Side	Main Shaft	MTLF	MTLFFXXX	MTLFMXXX
80	WT	Drive Train Module	Main Shaft Set	Low Speed Side	Radial Bearing	MTLR	MTLRFXXX	MTLRMXXX
81	WT	Drive Train Module	Main Shaft Set	Low Speed Side	Rotor Lock	MTLL	MTLLFXXX	MTLLMXXX
82	WT	Drive Train Module	Main Shaft Set	Low Speed Side	Slip Ring	MTLI	MTLIFXXX	MTLIMXXX
83	WT	Drive Train Module	Main Shaft Set	Mechanical Brake	-	MTB	MTBFXXX	MTBMXXX
84	WT	Drive Train Module	Main Shaft Set	Mechanical Brake	Calliper	MTBC	MTBCFXXX	MTBCMXXX
85	WT	Drive Train Module	Main Shaft Set	Mechanical Brake	Disk	MTBD	MTBDFXXX	MTBDMXXX
86	WT	Drive Train Module	Main Shaft Set	Mechanical Brake	Pad	MTBP	MTBPFXXX	MTBPMXXX
87	WT	Drive Train Module	Main Shaft Set	Mechanical Brake	Transmission Lock	MTBT	MTBTFXXX	MTBTMXXX
88	WT	Drive Train Module	Main Shaft Set	Sensors	-	MTS	MTSFXXX	MTSMXXX
89	WT	Drive Train Module	Main Shaft Set	Sensors	High Speed Sensor	MTSH	MTSHFXXX	MTSHMXXX
90	WT	Drive Train Module	Main Shaft Set	Sensors	Low Speed Sensor	MTSL	MTSLFXXX	MTSLMXXX
91	WT	Drive Train Module	Main Shaft Set	Sensors	Position Sensor	MTSP	MTSPFXXX	MTSPMXXX
92	WT	Electrical Module	-	-	-	EM	EMFXXX	EMMXXX

93	WT	Electrical Module	Auxiliary Electrical System	-	-	AE	AEFXXX	AEMXXX
94	WT	Electrical Module	Auxiliary Electrical System	Electrical Services	-	AEE	AEEFXXX	AEEMXXX
95	WT	Electrical Module	Auxiliary Electrical System	Electrical Services	24 DC Feeder	AEEF	AEEFFXXX	AEEFMXXX
96	WT	Electrical Module	Auxiliary Electrical System	Electrical Services	Auxiliary transformer	AEEA	AEEAFXXX	AEEAMXXX
97	WT	Electrical Module	Auxiliary Electrical System	Electrical Services	Breaker	AEEB	AEEBFXXX	AEEBMXXX
98	WT	Electrical Module	Auxiliary Electrical System	Electrical Services	Cabinet	AEEC	AEECFXXX	AEECMXXX
99	WT	Electrical Module	Auxiliary Electrical System	Electrical Services	Fan	AEEF	AEEFFXXX	AEEFMXXX
100	WT	Electrical Module	Auxiliary Electrical System	Electrical Services	fuse	AEEU	AEEUFXXX	AEEUMXXX

APPENDIX E. List of required modules for ERP-OWT

The design of an ERP software package for OWT was discussed in Chapter 5. This appendix lists the modules that are required for designing ERP-OWT from a wind turbine perspective.

1. **Financial Planning and Forecasting Management**
    a. Input and Output ledger entries
    b. Financial Analysis
    c. Management of Foreign Exchange rates
    d. Representation of Profit and Loss
    e. Cost Management
    f. Financial Strategy Development and Layout of Translation Process
    g. Planning, Budgeting and Forecasting
    h. Profitability and Cost Management
    i. Monitoring and Reporting
    j. Payments and Bank Communication
    k. Debt and Investment Management
    l. Financial Risk Management
    m. Asset Risk Management (Wind Turbines)
    n. Expense Management

2. **Accounts Management**
    a. Cash and Liquidity Management
    b. Accounts Payable and Receivable
    c. Advanced Cost Accounting
    d. Fixed Asset Accounting
    e. General Ledger
    f. Travel Management

g. Invoice Management
h. Receivable Management
i. Appreciation and Depreciation of cost of assets
j. Billing and Revenue Management
k. Credit Evaluation and Management
l. Dispute Resolution
m. Collections Management
n. Discount and Payment Term Optimisation
o. Document Retention and Archiving

3. **Asset Management**

a. Automatic generation of Codes for Components
b. Automatic generation of Codes for failures
c. Automatic generation of Codes for work order for service maintenance
d. Record of original component cost
e. Record of purchases and disposal of assets
f. Ability to simulate and analyse user defined relationships for conditions
g. Enterprise Risk Management
h. Productivity Planning and Scheduling
i. Costing of Projects
j. Asset Lifecycle Management
    i. Capital Asset Management
    ii. Equipment Cost Analysis
    iii. Resource Assignment
    iv. Condition Based Maintenance
    v. Planning for Maintenance
    vi. Management of maintenance

4. Inventory Management

a. Information about consumables and spares in the inventory

b. Record of inspection and maintenance of spares

c. Tracking of incoming and outgoing items from inventory

d. Management of optimal number of spares

5. Human Resource Management

a. Shaft management

b. Information about Personal and their key skillsets

c. Identifying need for training and development

d. Identifying insurance rules and plans

e. Determination of labour rate,

f. Advertisement and hiring of professionals (skilled and unskilled)

g. Training of personnel

6. Procurement Management

a. Automatic generation of Purchase Order

b. Handling of request for purchases

c. Handling of quotations from vendors

d. Maintain record of vendors (suppliers and service providers)

e. Tracking of items returned to the suppliers

f. Forecasting Demand

g. Demand Management

h. Forecasting Distribution

i. Deciding upon purchases, rental agreements, warranty

j. Handling of Lease Agreements for contracted items

k. Contracting support structures, like air and water transportation, etc.

l. Track changes in cost of labour, material and tools

m. Purchase Order Collaboration
n. Invoice Collaboration
o. Invoice Workflow and Approval Management
p. Response and Supply Management
q. Strategic Sourcing and Supplier Management
r. Direct Procurement
s. Service Procurement
t. Agreement Management

7. **Shareholder Management**
    a. Information about all shareholders
    b. Information about shareholders payments and instalments
    c. Meeting Organiser and associated arrangements
    d. Reporting to shareholders (periodic emails)
    e. Generation of reports about stocks and dividends

8. **Service Management**
    a. Service Agreements
    b. Service Monitoring
    c. Escalation Procedures
    d. Definition of Services
    e. Management of Planned Work
    f. Management of Unplanned Work
    g. Creation of Work Order
    h. Prioritise work orders
    i. Scheduling of work orders, task dependencies, work shifts
    j. Use dynamic condition monitoring methods to predict failure
    k. Transportation Management

9. **Health, Safety and Environment (HSE)**

   a. Ability to investigate accident, root cause of accident
   b. Identify incidences in which risk to safety may be possible
   c. Audit maintenance plan for issues with HSE
   d. Traceability into old incidences, work orders and remedial actions
   e. Traceability of regulatory compliance in new and old work orders
   f. Identify cost associated with regulatory compliance (if any)

10. **Analytics and Audit Management**

    a. Business Intelligence
    b. Enterprise Performance
    c. Governance, Risk and Compliance

11. **IT Management and Operations**

    a. Management of IT Infrastructure
    b. Data Warehousing
    c. Data Management
    d. Messaging Services
    e. Mobile Application
    f. Project Management

12. **Customer Services Management**

    a. Technical (Internal)
    b. Technical (External)
    c. Non-Technical (Internal)
    d. Non-Technical (External)

13. Reporting

a. Capital Asset Management

b. Health, Safety and Environment

c. Financials

d. Human Resources

e. Inventory Management

f. Procurement

g. Project Costing

h. Asset Management

i. Service Management

j. Transportation Management

k. Warehouse Management (Inventory)