DISSERTATION PAPER

Modelling System Failures to Optimise Wind Turbine Maintenance

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ABSTRACT
Modelling System Failures (MSF) is a unique quantitative maintenance optimisation technique which permits the evaluation of life-data samples and enables the design and simulation of the system's model to determine optimum maintenance activities. In this paper, the approach of MSF is used to assess the failure characteristics of a horizontal axis wind turbine. Field failure data are collated and analysed using the Maximum Likelihood Estimation in the Weibull Distribution; hence shape (β) and scale (η) parameters are estimated for critical components and subsystems of the wind turbine. Reliability Block Diagrams are designed to model the failures of the wind turbine and of a selected wind farm. The models are simulated to assess the reliability, availability and maintainability of the wind turbine and the farm; taking into account the costs and availability of maintenance crew and spares holding. Optimal maintenance activities are determined to minimise the total life-cycle cost of the wind farm.

Key words: Wind turbine, Failure Modelling, Reliability, Availability and Maintenance Optimisation

1. INTRODUCTION
Maintenance is indispensable to the core business objective of any industry that utilises physical assets. An appropriate maintenance strategy for wind turbines was selected in [1]. A *qualitative* maintenance optimisation technique known as Reliability Centred Maintenance was used in conjunction with an Asset Life-Cycle Analysis technique to assess the viability of the selected strategy over the life-cycle of the wind turbines. Arthur [2] and Scarf [3] observed that *qualitative* maintenance optimisation is often clouded with subjective opinion and experience, and further suggest the utilisation of *quantitative* methods to optimise the maintenance activities of physical assets. Andrawus et al [4] discussed the concept and relevance of two *quantitative* maintenance optimisation techniques and highlighted the applicability and the benefits to the wind energy industry.

Quantitative maintenance optimisation (QMO) techniques employ a mathematical model in which both the cost and benefits of maintenance are quantified and an optimum balance between both is obtained [5]. QMO is generally deemed to require large field failure data which are often unavailable [2]. As a result, life-failure data are seldom used to underpin the maintenance optimisation processes of physical assets. This practise has continued to jeopardise the inherent advantages of the quantitative maintenance optimisation and has contributed to the popularisation of the *qualitative* methods. Life-data unavailability is more

often than not a direct consequence of improper setting-up of data-bases and the lack of appropriate recording formats for failure and maintenance history [6]. Indeed, industries are known to spend very significant amounts of money on *Information Management Systems* to capture and store failure and maintenance data, but their format is typically not readily usable for optimisation tasks. Hence the value added from such systems has been very difficult to justify. Industries rarely strive to evaluate the data requirements for asset performance optimisation from the beginning of ownership and set-up databases to incorporate the appropriate recording format for all necessary information. The notion that huge volume of data are required to start the process of optimisation has remained a major barrier to practical implementation. Therefore, it is imperative to create a *baseline* to start the process with whatever data are available, so that a concerted effort can be made to continuously and progressively develop the baseline.

This paper presents a case study to optimise the maintenance activities of a 26 x 600 kW wind farm by using a quantitative maintenance optimisation approach known as *Modelling System Failures*.

2. METHODOLOGY

The Modelling System Failures (MSF) technique permits the evaluation of life-data samples and enables the design and simulation of the system's model to determine optimum maintenance activities. Field failure-data of 600 kW horizontal axis wind turbines are collated. Maximum Likelihood Estimation (MLE) in the Weibull distribution is used to analyse the collated data to estimate *shape* (β) and *scale* (η) parameters of critical components and subsystems of the turbine. The reader is referred to [4, 7-8] for a detailed study on the concept, relevance and applicability of the Maximum Likelihood Estimation method in the Weibull distribution. The value of β describes the failure pattern of the equipment. As a general rule, (β <1) means a reducing failure pattern, (β=1) signifies a constant failure pattern and (β>1) indicates an increasing failure pattern. Conversely, the scale parameter (η) denotes the characteristic life of the equipment; the time at which there is an approximately 0.632 probability that the equipment will have failed [8].

The reducing failure pattern (β<1), usually known as the *infant mortality*, denotes failures that occur at the early-life of equipment and the likelihood of occurrence reduces as the age of the equipment increases. The constant failure pattern (β=1) represents failures that are independent of equipment age, that is, the likelihood of occurrence is invariable throughout the life-cycle of the equipment. Lastly, the increasing failure pattern (β>1), commonly referred to as *wear-out*, symbolises failures that occur at the later life of equipment; the likelihood of occurrence increases with the age of the equipment. It is worth noting that equipment usually exhibits the three basic patterns of failure at different stages of their life. Thus fitting failure distribution to single β and η is not a one-off procedure but a continuous process which requires periodic evaluation.

'ReliaSoft Weibull ++7' software [9], which is based on the fundamental mathematical principles presented in [4, 7-8], is used to analyse the collated data. The software calculates automatically the β and η parameters of the Weibull distribution and generates a number of graphs such as the *Weibull probability plots, reliability graphs, failure verses time plots, probability density function graphs, etc.* The estimated values of β and η of each component within a subsystem of the wind turbine are used to design Reliability Block Diagrams (RBD) to model the failures of the subsystem. The β and η values of each subsystem of the wind turbine are used to design RBD to model the failures of the turbine. This is used in modelling

the failure characteristics of the wind farm. The models are simulated using 'ReliaSoft BlockSim-7' [10] to assess the reliability, availability and maintainability (RAM) of the wind turbine and the wind farm by taking into account the costs and availability of maintenance crew and spares holding.

3. A CASE STUDY

This section presents a case study to demonstrate the practical application of the Modelling System Failures approach to optimise the maintenance activities of a 26 x 600 kW wind farm.

3.1 Data Collation

Historical failure data pertinent to the critical components and subsystems of the particular type of 600 kW wind turbine were extracted from Supervisory Control and Data Acquisition (SCADA) systems over a period of 9 years. The SCADA systems record failures with the date and time of occurrence; this was used in conjunction with maintenance Work Orders (WOs) of the same period to ascertain the specific type of failure and the components involved. The collated data were grouped according to subsystems and components of the wind turbine and then re-arranged in order of failure modes and dates.

The work presented in this paper focuses on the life-failure data of one type of 600 kW horizontal axis wind turbine. Tables 1, 2, 3 and 4 contain the field failure data of the main shaft, main bearings, gearbox and the generator respectively. In order to evaluate the wind farms in anonymity, they were labelled alphabetically (*A* to *Y*); *WF-C* in Table 1, column 1 denotes *Wind Farm C*. Individual wind turbines were named according to their respective wind farms; *WF-A-WT-10* (Table 2, column 2) denotes *Wind Farm A-Wind Turbine number 10*. The manufacturers of the failed components were numbered and recorded in column 3 of tables 1-4. *The fail-date and fail-time from the base-date* as well as the *causes of failure* are recorded in the same tables.

Table 1. Main shaft failure data

Wind Farm (WF)	Wind Turbine (WT)	Component Manufacturer	Fail date dd/mm/yyyy	Fail time (days)	Main shaft	Causes of failure
WF-C	WF-C-WT-13	2	"19/11/2003"	315	F	Other
WF-K	WF-K-WT-7	5	"01/03/2004"	424	F	Poor design
WF-F	WF-F-WT-16	1	"07/05/2004"	492	F	Unknown
WF-A	WF-A-WT-27	1	"13/06/2004"	529	F	Fatigue
WF-L	WF-L-WT-3	7	"29/12/2004"	698	F	Fatigue
WF-N	WF-N-WT-3	2	"25/07/2005"	936	F	Fatigue
WF-M	WF-M-WT-3	7	"14/06/2006"	1233	F	Fatigue

Table 2. Main bearings failure data

Wind Farm (WF)	Wind Turbine (WT)	Component Manufacturer	Fail date dd/mm/yyyy	Fail time (days)	Main Bearings	Causes of failure
WF-A	WF-A-WT-10	1	"29/01/2003"	29	F	Poor design
WF-B	WF-B-WT-4	2	"09/05/2003"	129	F	Poor design
WF-A	WF-A-WT-13	1	"19/05/2003"	139	F	Poor design
WF-A	WF-A-WT-3	1	"27/06/2003"	178	F	Poor design
WF-C	WF-C-WT-4	2	"31/07/2003"	212	F	Unknown
WF-D	WF-D-WT-13	1	"05/11/2003"	309	F	Unknown
WF-A	WF-A-WT-34	4	"10/02/2004"	406	F	Fatigue
WF-E	WF-E-WT-2	3	"15/05/2004"	500	F	Poor design
WF-A	WF-A-WT-22	1	"15/12/2004"	714	F	Fatigue
WF-D	WF-D-WT-13	1	"27/12/2004"	726	F	Fatigue
WF-A	WF-A-WT-26	1	"17/01/2005"	747	F	Fatigue
WF-A	WF-A-WT-34	3	"18/01/2005"	748	F	Fatigue

Table 3. Gearbox failure data

Wind Farm (WF)	Wind Turbine (WT)	Component Manufacturer	Fail date dd/mm/yyyy	Fail time (days)	HSS bearing	IMS bearing	Gear wheels	Key way	Gearbox catastrophic	Causes of failure
WT-F	WF-F-WT-1	8	"24/11/1999"	329	F	S	S	S	F	"Unknown"
WT-F	WF-F-WT-18	8	"13/01/2000"	378	F	S	F	F	F	"Fatigue"
WT-F	WF-F-WT-24	8	"26/03/2001"	815	F	S	S	F	F	"Fatigue"
WT-F	WF-F-WT-07	8	"23/07/2001"	934	F	S	S	F	S	"Fatigue"
WT-F	WF-F-WT-15	8	"19/11/2001"	1043	F	S	F	S	S	"Fatigue"
WF-A	WF-A-WT-8	9	"05/05/2003"	1585	F	F	S	S	S	"Fatigue"
WF-A	WF-A-WT-14	9	"06/06/2003"	1649	F	F	S	S	S	"Fatigue"
WF-A	WF-A-WT-23	9	"04/08/2003"	1676	F	S	S	S	S	"Fatigue"
WF-A	WF-A-WT-9	9	"27/08/2003"	1699	F	F	S	S	S	"Fatigue"
WF-B	WF-B-WT-6	9	"11/09/2003"	1714	F	F	S	S	S	"Fatigue"
WF-B	WF-B-WT-10	9	"04/11/2003"	1768	S	S	S	S	S	"Fatigue"
WF-B	WF-B-WT-6	10	"04/11/2003"	1768	S	S	S	S	S	"Fatigue"
WF-B	WF-B-WT-14	9	"22/11/2003"	1786	S	S	S	S	S	"Fatigue"
WF-F	WF-F-WT-19	9	"18/06/2004"	1985	S	S	F	S	S	"Fatigue"
WF-G	WF-G-WT-9	9	"30/06/2004"	2006	F	F	S	S	F	"Unknown"
WF-A	WF-A-WT-33	8	"09/10/2004"	2107	S	S	F	S	F	"Fatigue"
WF-A	WF-A-WT-1	8	"18/10/2004"	2116	S	S	S	S	S	"Fatigue"
WF-A	WF-A-WT-19	8	"30/10/2004"	2128	S	S	S	S	S	"Fatigue"
WF-C	WF-C-WT-7	11	"01/11/2004"	2130	F	S	F	S	S	"Fatigue"
WF-D	WF-D-WT-20	10	"04/02/2005"	2225	S	S	F	S	S	"Poor design"
WF-A	WF-A-WT-19	10	"02/04/2005"	2282	S	S	F	S	S	"Poor design"
WF-D	WF-D-WT-2	8	"11/05/2005"	2321	S	S	S	S	S	"Poor design"

Note that table 4 shows additional information about the serial numbers of the failed generators. This information is essential to identify re-occurring failure modes and to effectively trace the failure history of each component or subsystem of the wind turbine. To illustrate the importance of the additional information, consider the failure data recorded in row 3 of table 4. A generator with a serial number *GSN-2* failed in wind turbine 22 of wind farm F. Also in row 4 of the table, another generator failure is recorded with a serial number *GSN-2* but this time in wind turbine 15 of the same wind farm. It will be noticed that the serial numbers of the generators are the same, indeed, it is the same generator. The first failure of the generator in wind turbine 22 was due to bearing failure, it was removed for repairs and the turbine was fitted with a spare. The failed generator (*GSN-2*) was repaired and transferred into the spare pool. The generator in wind turbine 15 failed and it was fitted with the *GSN-2* from the spare pool. The generator (*GSN-2*) eventually failed catastrophically as a result of a stator winding failure. A similar failure event is recorded in rows 9-11 of the table. It is worth noting that this type of detailed recording of failure data was found only in wind farm F and is specific to the generators.

3. 2 Results and Discussion

This subsection presents the results and discussion of the practical application of the modelling system failures technique to optimise the maintenance activities of an existing 26 x 600 kW wind farm.

3.2.1 Shape and Scale Parameters

The result of the shape (β) and scale (η) parameters as estimated by the ReliaSoft Weibull ++7 software are presented in Table 5. The probability distribution and the parameter estimation technique are shown in columns 3 and 4 of the table respectively. In the analysis, the Fisher Matrix (FM) confidence bound method and median (MED) ranking was used to underpin the statistical evaluation.

Table 4. Generator failure data

Farm (WF)	Wind Turbine (WT)	Serial number	Component Manufacturer	Fail date dd/mm/yyyy	Fail time (days)	Windings	Bearings	Generator catastrophic	Causes of failure
WF-F	WF-F-WT-1	GSN-1	4	"24/02/1997"	55	S	S	F	Fatigue
WF-F	WF-F-WT-22	GSN-2	4	"15/02/1998"	411	S	F	S	Fatigue
WF-F	WF-F-WT-15	GSN-2	4	"01/06/2000"	424	F	S	F	Fatigue
WF-F	WF-F-WT-15	GSN-3	4	"01/03/1999"	789	S	F	S	Fatigue
WF-F	WF-F-WT-18	GSN-4	4	"01/06/1999"	881	S	F	S	Other
WF-F	WF-F-WT-12	GSN-5	4	"01/12/2000"	548	S	S	F	Other
WF-F	WF-F-WT-12	GSN-6	4	"01/10/1999"	1003	F	S	S	Poor Design
WF-F	WF-F-WT-17	GSN-7	4	"15/12/1999"	1080	F	S	S	Unknown
WF-F	WF-F-WT-15	GSN-7	4	"01/01/2002"	746	F	S	S	Poor Design
WF-F	WF-F-WT-15	GSN-7	4	"01/07/2002"	181	F	S	S	Poor Design
WF-F	WF-F-WT-5	GSN-8	4	"08/01/2000"	1307	S	F	S	Fatigue
WF-F	WF-F-WT-24	GSN-9	4	"08/01/2000"	1307	S	S	F	Poor Design
WF-F	WF-F-WT-16	GSN-10	4	"01/11/2000"	1399	S	F	S	Poor Design
WF-F	WF-F-WT-7	GSN-11	4	"01/06/2002"	1977	S	F	S	Poor Design
WF-D	WF-D-WT-26	GSN-12	4	"21/01/2003"	2211	S	F	S	Fatigue
WF-A	WF-A-WT-29	GSN-13	4	"29/01/2003"	2219	S	F	S	Fatigue
WF-A	WF-A-WT-20	GSN-14	4	"09/04/2003"	2289	S	F	S	Fatigue
WF-C	WF-C-WT-11	GSN-15	4	"09/05/2003"	2319	S	F	S	Fatigue
WF-A	WF-A-WT-18	GSN-16	4	"09/06/2003"	2349	F	S	S	Fatigue
WF-A	WF-A-WT-8	GSN-17	4	"24/06/2003"	2364	S	F	S	Fatigue
WF-D	WF-D-WT-4	GSN-18	4	"07/08/2003"	2409	S	F	S	Fatigue
WF-D	WF-D-WT-2	GSN-19	4	"28/08/2003"	2430	F	S	S	Fatigue
WF-D	WF-D-WT-27	GSN-20	4	"15/09/2003"	2445	S	F	S	Fatigue
WF-A	WF-A-WT-21	GSN-21	4	"11/11/2003"	2535	F	F	F	Fatigue
WF-H	WF-H-WT-11	GSN-22	4	"13/11/2003"	2537	S	F	S	Fatigue
WF-A	WF-A-WT-7	GSN-23	4	"29/12/2003"	2553	S	F	S	Fatigue
WF-A	WF-A-WT-20	GSN-24	4	"29/01/2004"	2584	S	F	S	Other
WF-C	WF-C-WT-8	GSN-25	4	"04/03/2004"	2618	S	F	S	Other
WF-E	WF-E-WT-20	GSN-26	4	"25/03/2004"	2639	F	S	S	Poor Design
WF-F	WF-F-WT-20	GSN-27	4	"25/03/2004"	2639	S	S	S	Unknown
WF-I	WF-I-WT-1	GSN-28	4	"20/04/2004"	2665	S	F	S	Poor Design
WF-D	WF-D-WT-15	GSN-29	4	"23/04/2004"	2668	S	S	S	Fatigue
WF-A	WF-A-WT-1	GSN-30	4	"04/05/2004"	2679	F	F	F	Poor Design
WF-D	WF-D-WT-27	GSN-31	4	"07/05/2004"	2682	S	F	S	Poor Design
WF-E	WF-E-WT-4	GSN-32	4	"18/06/2004"	2724	S	F	S	Poor Design
WF-I	WF-I-WT-6	GSN-33	4	"26/06/2004"	2732	S	F	S	Poor Design
WF-G	WF-G-WT-9	GSN-34	4	"08/07/2004"	2744	S	S	S	Other
WF-A	WF-A-WT-29	GSN-35	4	"13/07/2004"	2749	S	F	S	Poor Design
WF-A	WF-A-WT-17	GSN-36	4	"16/07/2004"	2752	S	F	F	Poor Design
WF-C	WF-C-WT-19	GSN-37	4	"30/07/2004"	2766	S	S	S	Poor Design
WF-C	WF-C-WT-10	GSN-38	4	"12/08/2004"	2779	S	S	F	Poor Design
WF-E	WF-E-WT-11	GSN-39	4	"17/09/2004"	2815	S	F	S	Poor Design
WF-D	WF-D-WT-28	GSN-40	4	"21/09/2004"	2819	S	F	S	Poor Design
WF-E	WF-E-WT-16	GSN-41	4	"25/10/2004"	2853	F	S	S	Fatigue
WF-E	WF-E-WT-13	GSN-42	4	"07/11/2004"	2866	F	S	S	Fatigue
WF-I	WF-I-WT-7	GSN-43	4	"29/12/2004"	2918	F	S	S	Poor Design
WF-A	WF-A-WT-24	GSN-44	4	"02/01/2005"	2922	F	S	S	Poor Design
WF-A	WF-A-WT-6	GSN-45	4	"28/02/2005"	2969	F	F	F	Poor Design
WF-I	WF-I-WT-13	GSN-46	4	"07/04/2005"	3007	S	F	S	Poor Design
WF-A	WF-A-WT-19	GSN-47	4	"26/04/2005"	3026	S	F	S	Poor Design
WF-J	WF-J-WT-9	GSN-48	4	"12/09/2005"	3165	S	F	S	Poor Design

Table 5 Shape and scale parameters for wind turbines critical subsystems

Sub-system	Components	Distribution	Analysis	Shape (β)	Scale (η)	Likeli-hood	Failed	Suspended	Mean Life
Blade									
Main shaft		Weibull-2P	MLE	1.43	6389	-72.90	7	70	5807
Main bearing		Weibull-2P	MLE	1.09	3835	-112.79	12	65	3711
Gearbox	——	Weibull-2P	MLE	1.05	29051	-56.99	5	72	28521
	Gears	Weibull-2P	MLE	2.50	5715	-75.10	7	70	5070
	HSS bearings	Weibull-2P	MLE	1.52	7244	-125.00	12	64	6528
	IMS bearings	Weibull-2P	MLE	3.63	4694	-53.99	5	72	4232
	Key way	Weibull-2P	MLE	0.84	101790	-35.69	3	74	111720
Generator	——	Weibull-2P	MLE	1.11	17541	-98.70	9	68	16888
	Bearings	Weibull-2P	MLE	3.35	3599	-283.98	31	46	3231
	Windings	Weibull-2P	MLE	1.78	6574	-154.62	15	62	5850

The estimated values of β and η for the gearbox are 1.05 and 29051 days respectively. The β value of 1.05 indicates a *random failure pattern* while the η value of 29051 implies that there is an approximate probability of 0.632, that all the gearboxes in a wind farm of 600 kW turbines would have failed within 29051 days or 79 years, given the assessed failure behaviour of the gearbox and the current maintenance strategy employed. The *Weibull probability plot* (graphical data analysis) of this failure characteristic at 95% confidence bound is shown in Figure 1. *The probability density function (pdf)* and the *failure rate* plots are shown in Figures 2 and 3 respectively. The pdf plot is skewed to the left. The failure rate plot shows a horizontal line which explains the randomness of the failure pattern of the gearbox. The generator and the main bearing exhibit random failure pattern with β values of 1.11 and 1.09 respectively.

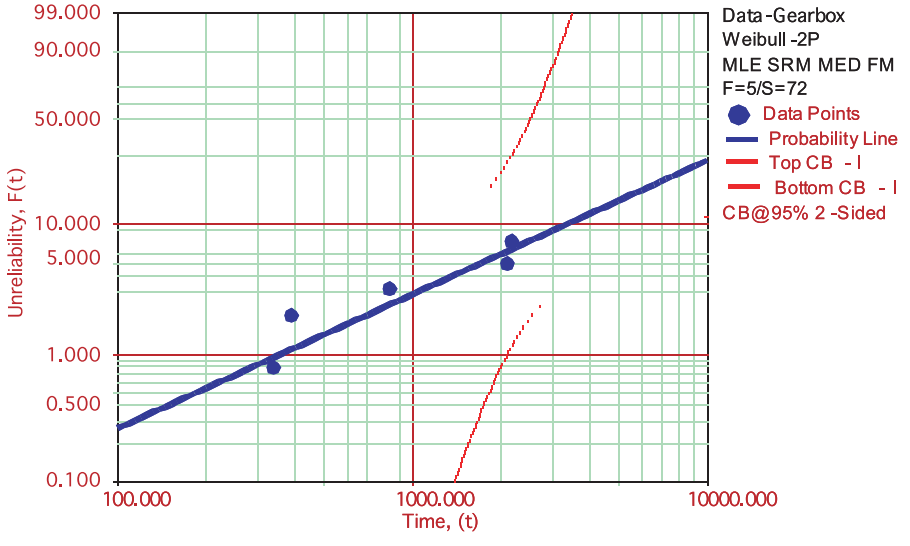


Figure 1. Weibull-probability plot of gearbox

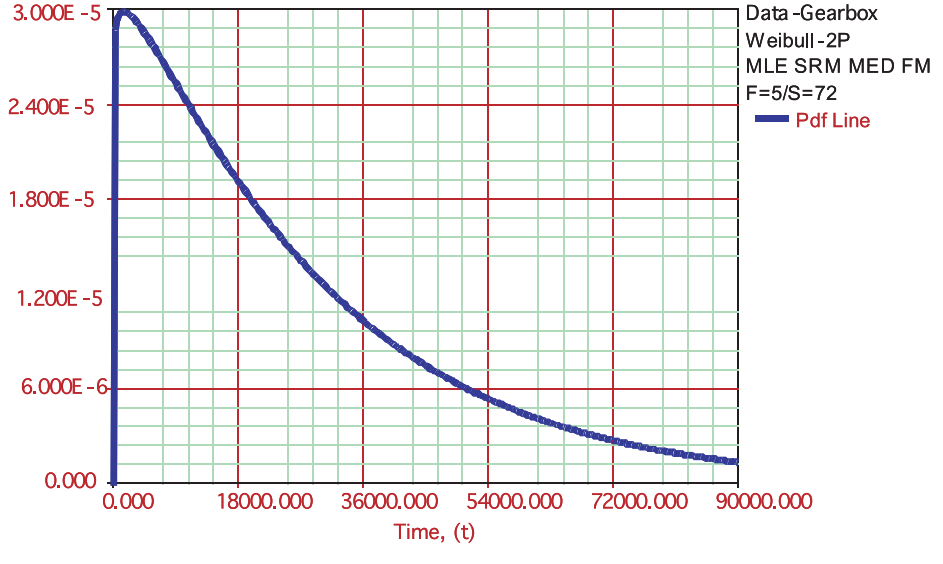


Figure 2. Weibull-probability density function plot for gearbox

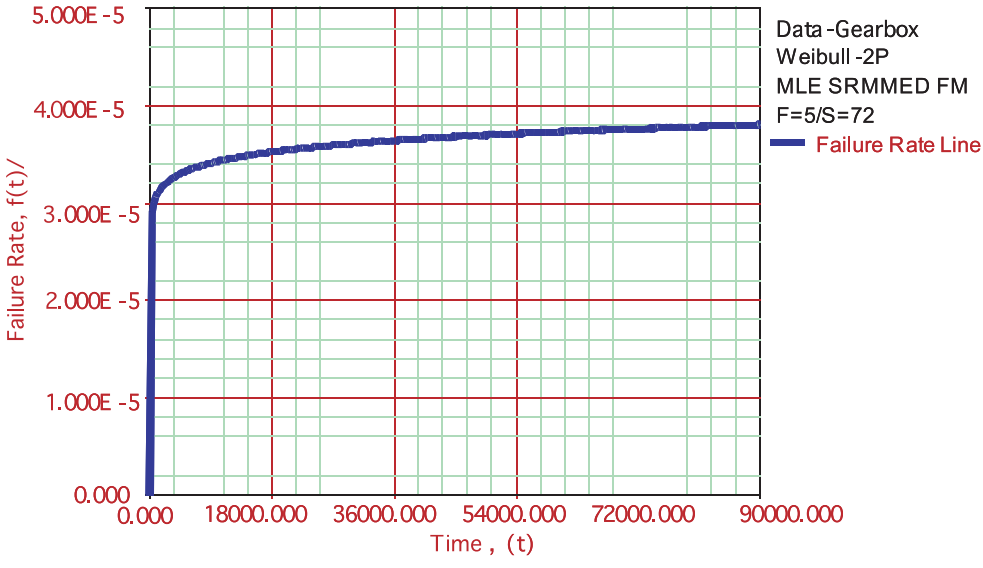


Figure 3. Weibull-failure rate plot for gearbox

The gear-wheels, intermediate stage (IMS) bearing of the gearbox, the stator winding and bearings of the generator have β values of 2.50, 3.63, 1.78 and 3.35 respectively. These indicate a *wear-out failure pattern*. The key-way of the gearbox has a β value of 0.8 which denotes an *in-born failure pattern or infant mortality.*

3.2.2 Reliability Trend

Table 6 presents the reliability trend of critical subsystems of the wind turbine over a period of 20 years. The table shows the upper and the lower limits of the reliabilities at 95% confidence bound. The reliability of the main-shaft reduces from 0.98 in the first year to about 0.30 at the end of the 20 years life-cycle. The lower limit of the reliability reduces significantly from 0.93 in the first year to 0.25 in the 9th year and subsequently to about 0.01 at the end of the 15th year. On the other hand, the reliability of the main bearing reduces from 0.93 in the first year to about 0.53 in the 7th year and further degenerates to about 0.13 at the end of the 20 years life-cycle. The lower limit reduces from 0.86 in the first year to 0.00 at end of the 15th year.

The reliability of the gearbox reduces from 0.98 in the first year to about 0.67 at the end of the 7th year and further degenerates to 0.32 in the 11th and 0.00 in the 20th year. The lower limit of the reliability reduces to 0.16 in the 10th year and 0.00 in the 13th year. The reliability of the generator reduces from 0.98 in the first year to 0.34 and 0.01 in the 9th and 15th year respectively. The lower limit deteriorates to 0.00 in the 13th year from 0.94 in the first year. The rapid dilapidation of the reliabilities of the subsystems as they advance in age requires a serious adjustment in the current maintenance strategies employed to maintain them.

Figure 4 shows the reliability trend of the critical subsystems. Assuming a reliability of 0.95 is desired as a minimum threshold, it is worth noting that the subsystems (main bearing, main shaft, gearbox and the generator) will fall below this target in year 3, 1, 2 and 3 respectively, given the current failure behaviour and the maintenance strategy employed.

3.2.3 Maintenance Optimisation

Maintenance optimisation denotes the best possible balance between costs, risks and performance. As a general rule, *Condition-based maintenance (CBM)* (corrective maintenance based on inspection) is suitable for components or subsystems with a *random*

Table 6. Reliability trend for critical subsystems of a 600 kW wind turbine

	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Main Shaft	Reliability	0.98	0.96	0.92	0.89	0.85	0.80	0.76	0.72	0.68	0.64	0.60	0.56	0.52	0.48	0.45	0.41	0.38	0.35	0.33	0.30
	Upper	1.00	0.98	0.96	0.94	0.93	0.92	0.91	0.90	0.90	0.89	0.89	0.88	0.88	0.87	0.87	0.86	0.86	0.86	0.85	0.85
	Lower	0.93	0.89	0.84	0.77	0.67	0.57	0.45	0.35	0.25	0.17	0.11	0.07	0.04	0.02	0.01	0.01	0.00	0.00	0.00	0.00
Main bearings	Reliability	0.93	0.85	0.78	0.71	0.64	0.58	0.53	0.48	0.43	0.39	0.35	0.31	0.28	0.25	0.23	0.21	0.18	0.17	0.15	0.13
	Upper	0.96	0.91	0.87	0.84	0.82	0.80	0.78	0.76	0.75	0.74	0.72	0.71	0.70	0.69	0.68	0.67	0.66	0.65	0.65	0.64
	Lower	0.86	0.75	0.62	0.49	0.37	0.27	0.19	0.13	0.08	0.05	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Gearbox	Reliability	0.98	0.94	0.90	0.86	0.80	0.74	0.67	0.59	0.50	0.41	0.32	0.24	0.17	0.11	0.07	0.04	0.02	0.01	0.00	0.00
	Upper	0.99	0.97	0.94	0.91	0.87	0.82	0.77	0.73	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
	Lower	0.93	0.88	0.84	0.79	0.72	0.65	0.55	0.43	0.29	0.16	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Generator	Reliability	0.98	0.95	0.91	0.85	0.77	0.68	0.57	0.45	0.34	0.23	0.14	0.09	0.05	0.02	0.01	0.00	0.00	0.00	0.00	0.00
	Upper	0.99	0.98	0.95	0.90	0.84	0.75	0.65	0.55	0.45	0.36	0.29	0.24	0.20	0.17	0.16	0.16	0.16	0.16	0.16	0.16
	Lower	0.94	0.90	0.85	0.77	0.69	0.59	0.48	0.36	0.24	0.14	0.07	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

failure pattern (i.e. β=1) except where failure consequences will not result in revenue losses, customer dissatisfaction or health, safety and environmental impact [1]. *Time-based maintenance (TBM)* is suitable for components and subsystems exhibiting a *wear-out failure pattern* (i.e. β>1). *Failure-based maintenance (FBM)* (corrective actions performed upon failure of the subsystems) is appropriate for components and subsystems with negligible failure consequences. Thus, given the failure patterns of the subsystems in table 5, Condition-Based Maintenance (CBM) is the most suitable strategy for maintaining the main bearing, gearbox and the generator. A CBM strategy constitutes maintenance tasks being carried out in response to the deterioration in the condition or performance of an asset or component as indicated by a condition monitoring process. The strategy enables the detection of "hidden" failures (such as incipient components failure) that can potentially cause catastrophic failure

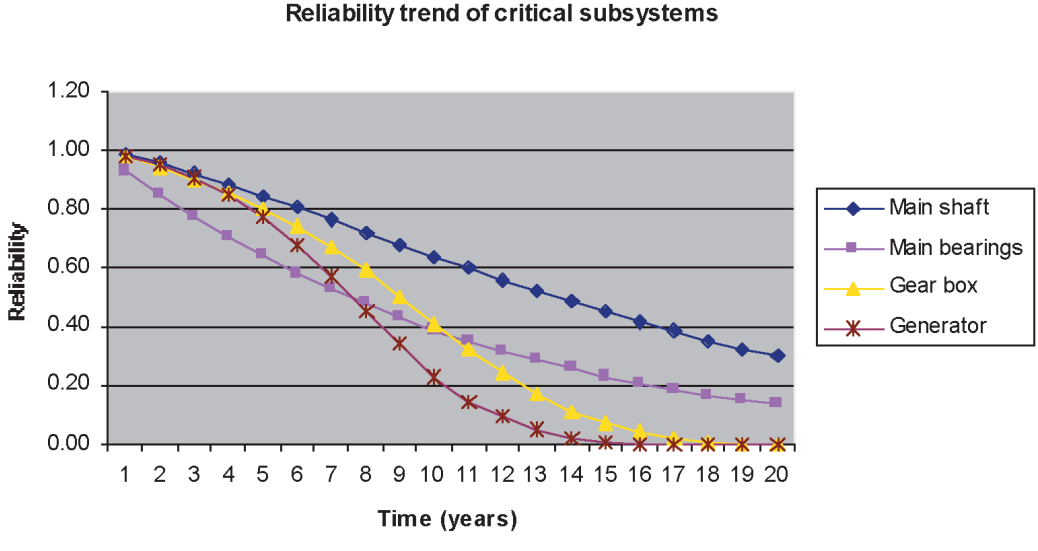


Figure 4. Reliability trends of critical subsystems over life-cycle

of the subsystems. *Time-based* as well as *corrective actions based on unanticipated failures* are suitable for maintaining the main shaft.

Spare pool policy is presented in Table 8, Corrective maintenance crew policy in Table 9, and inspection and preventative maintenance (PM) crew policy in Table 10. Note that the tables are developed based on discussion with collaborating wind farm operators to initiate the process of quantitative maintenance optimisation. The reader is referred to [1] for a detailed breakdown of the *direct cost per item* in table 8 and the *failure consequence* in table 9

3.2.4 Optimisation of Time-Based Maintenance Tasks

Table 5 shows some of the individual components of the gearbox and generator which exhibit a wear out failure pattern; hence time-based maintenance would be appropriate for these components. In this subsection we will assess the optimum cost and time to carry out the TBM tasks.

• The Gearwheels

The failure consequences or unplanned replacement of critical components and subsystems of the 600 kW wind turbine were determined and presented in Table 9. Using the cost of planned and unplanned replacement of the gearwheels, the optimal replacement time and cost are determined as shown in Figure 5. The minimum point on the curve in Figure 5 is 6.7003 which represent the optimal point. The optimal cost per unit time is £6.7003 and the optimal interval is at 2190 days (6 years). For comparison purposes, the cost of PM must be reduced to a common unit such as cost/year. Thus, the PM cost/year at the optimal point is the product

Start Time (days):	365	Cost of planned replacement:	£8,182
Increment (days):	365	Cost of unplanned replacement:	£78,468

Time Units	Cost/ Unit Time
365	22.622
730	11.790
1095	8.5382
1460	7.2386
1825	6.7548
2190	6.7003
2555	6.9034
2920	7.2731
3285	7.7542
3650	8.3093
4015	8.9110
4380	9.5375
4745	10.171
5110	10.797
5475	11.402
5840	11.977
6205	12.513
6570	13.003
6935	13.443
7300	13.831
7665	14.167

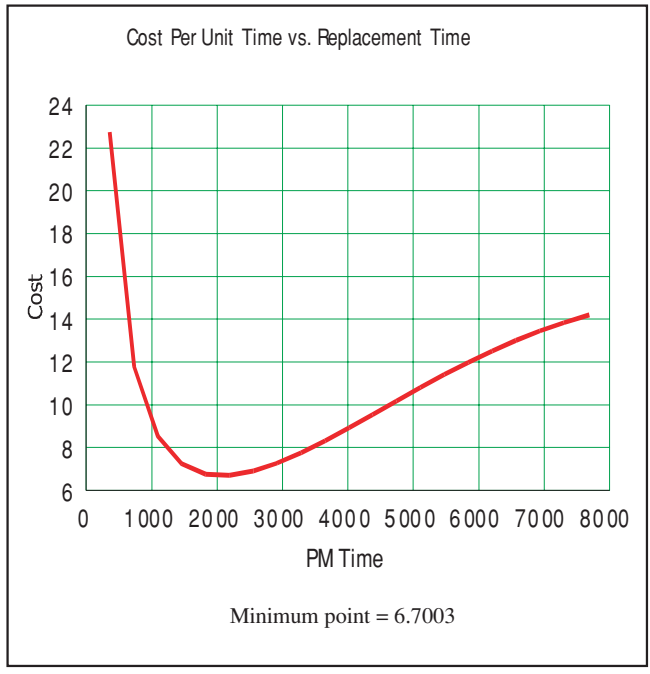


Figure 5. Gearwheels Optimum Replacement

Table 7. Reliability and probability of failure of a 600 kW wind turbine

Time (days)	Reliability	Prob. of failure	Failure rate x 10^{-3}
365	0.83	0.17	0.60
730	0.65	0.35	0.80
1095	0.48	0.52	0.90
1460	0.33	0.67	1.10
1825	0.21	0.79	1.30
2190	0.13	0.87	1.40
2555	0.08	0.92	1.60
2920	0.04	0.96	1.80
3285	0.02	0.98	2.00
3650	0.01	0.99	2.20

Table 8. Spare pool policy

Subsystem	Direct cost per item (£)	Indirect cost per year (£)	Initial stock level	Restock when stock level drops to	Number of stock to be added	Total Initial stock cost (£)
Mean bearings	9,851	100	4	2	2	39,804
Main shaft	11,133	100	2	1	1	22,466
Gear box	61,687	100	1	0	1	61,787
Generator	23,441	100	2	1	1	47,082

Table 9. Crew policy for corrective maintenance as a result of catastrophic failures

Subsystem	Repair Time (days)	Crew A (Person)	Labour cost/ hour (£)	Work hours/ day	Tasks crew can perform at the same time	Labour Cost per incident (£)	Direct cost per item (£)	Cost of access (£)	Production losses (£)	Failure Consequence (£)
Mean bearings	Mean (μ) = 2 Deviation (σ) = 1	3	50	8	1	2,400	9,851	8,460	1,663	22,375
Main shaft	μ = 4 σ = 1	3	50	8	1	4,800	11,133	11,280	1,900	29,114
Gearbox	μ = 3 σ = 1	3	50	8	1	3,600	61,687	11,280	1,900	78,468
Generator	μ = 2 σ = 1	3	50	8	1	2,400	23,441	8,460	1,663	35,964

Table 10. Crew policy for inspection and preventive maintenance

Subsystem	Task	Fixed interval (days)	Crew B (Person)	Labour cost/ hour (£)	Task duration (hours)	Labour Cost per Task (£)	Total cost of task (£)
Mean bearings	CBM (Inspection)	180	2	50	1.33	133	133
Main shaft	TBM (PM)	3650	2	50	1.33	133	133
Gearbox	CBM (Inspection)	180	2	50	2	200	200
Generator	CBM (Inspection)	180	2	50	1.6	160	160

of the cost per unit time (6.7003) and the number of days in a year (365) to give £2,445.61. In table 5, the estimated *Mean-Life* of the gearwheels is 5070 days. The Mean-Life denotes Mean-Time-To-Failure (MTTF) for non-repairable equipment or Mean-Time-Between-Failures (MTBF) for repairable equipment. PM tasks are often schedule at MTTF. However, the cost/year at the Mean-Life should be determined and compared with the optimal point. In Figure 5, the unit cost at 5070 days is about £10.8679. Thus, the PM cost/year at the Mean-Life is approximately £3,966.78. This is about 62% higher than the cost/year at the optimum interval. Alternatively, about £1,521.17 will be saved per PM task if it is carried out at the optimum interval.

• The Generator bearing

Figure 6 shows the optimisation plot for the generator bearing. The minimum point on the curve in the figure is 2.70292 which represent the optimal cost per unit time. The optimal interval for performing the PM task is 1095 days (3 years). The optimal cost/year is £986.23. The estimated Mean-Life of the generator bearing is 3231 days (Table 5) while its cost per unit time is 6.9026. The cost/year for doing the PM task at the MTTF is £2,519.46.

It is worth noting that the gearwheels, the IMS and HSS bearings are components of the gearbox. The gearbox failure is characterised by a random failure pattern as indicated by the estimated shape parameter and the failure rate plot in Table 5 and Figure 3 respectively. The gearbox is a repairable subsystem, thus the failure characteristic of the subsystem in this case will override the PM tasks for the individual components due to its random pattern of failure. Similar conditions apply to the generator with a shape parameter of 1.11.

• The Main Shaft

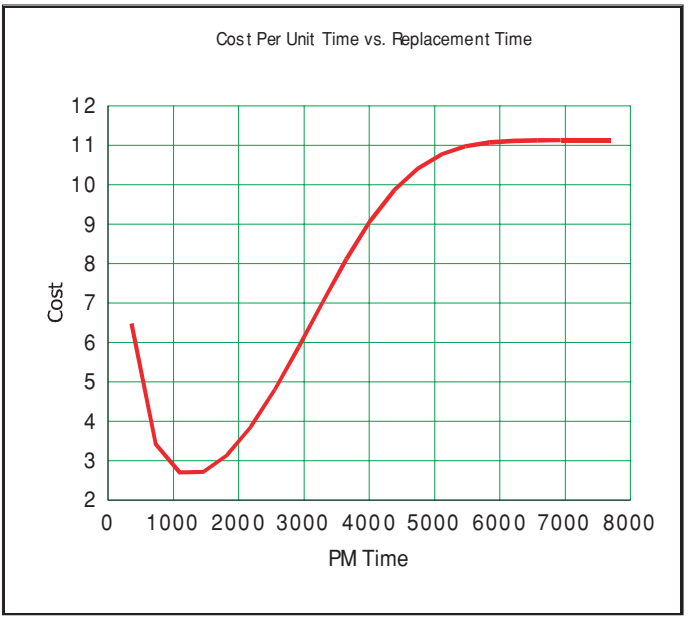
The shape parameter (β) for the main shaft in Table 5 shows a wear-out failure pattern. The cost for planned replacement of the main shaft is about £12,885 while the cost for unplanned replacement is £29,114. Figure 7 shows no optimum cost and interval for performing a TBM task on the main shaft. The cost per unit time decreases continuously with increases in time. The estimated Mean-Life of the main shaft is about 5807 days.

3.2.5 Failure Modelling

The estimated values of β and η are used to model the failures of the 600 kW wind turbine and the 26 x 600 kW wind farm. In the modelling, Reliability Block Diagrams are designed for the subsystems to incorporate the failure characteristics of their components. Then, the RBD of the subsystems are used to model the failures of the wind turbine. This is further used to model the failures of the wind farm.

Start Time (days):	365	Cost of planned replacement:	£2,332
Increment (days):	365	Cost of unplanned replacement:	£35,964

Time Units	Cost/ Unit Time
365	6.432
730	3.416
1095	2.702
1460	2.716
1825	3.143
2190	3.866
2555	4.805
2920	5.885
3285	7.018
3650	8.111
4015	9.078
4380	9.854
4745	10.41
5110	10.77
5475	10.97
5840	11.06
6205	11.10
6570	11.12
6935	11.12
7300	11.12
7665	11.12



Minimum = 2.702924499

Figure 6 Generator Bearings Optimum Replacement

Start Time:	365	Cost for planned replacement:	£12,885
Increment:	365	Cost for unplanned replacement:	£29,114

Time Units	Cost/Unit Time
365	36.29810
730	18.98762
1095	13.35339
1460	10.61503
1825	9.02437
2190	8.00153
2555	7.29934
2920	6.79491
3285	6.42041
3650	6.13540
4015	5.91432
4380	5.74026
4745	5.60160
5110	5.49013
5475	5.39985
5840	5.32632
6205	5.26618
6570	5.21684
6935	5.17627
7300	5.14288
7665	5.11540

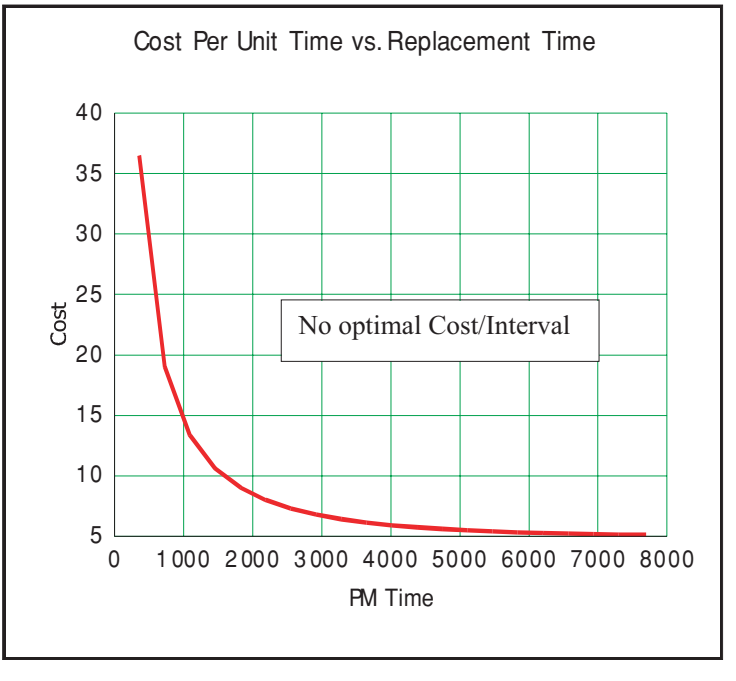


Figure 7. Main Shaft Optimum Replacement

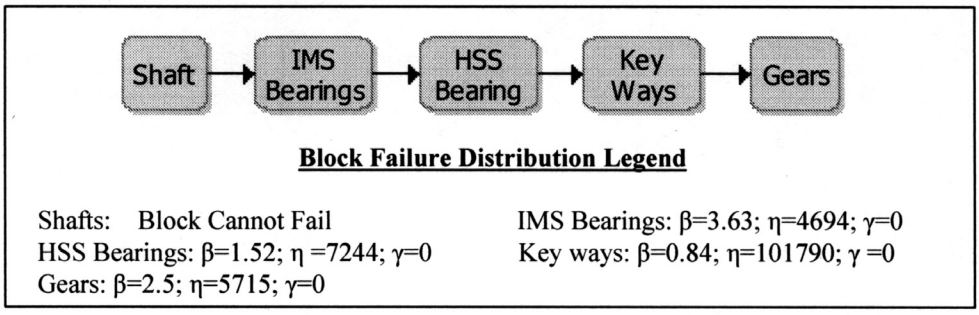


Figure 8. Reliability Block Diagram of a gearbox

Figure 8 shows the Reliability Block Diagram of a typical gearbox in the 600 kW horizontal axis wind turbine. The components are connected in *series* and the estimated β and η values of each component are incorporated into the RBD. Note that any component whose failure data are not available has been set to *'block cannot fail'* in the models. This is to avoid subjective and illogical assumptions about the components, and to ensure the modelling is based solely on field failure data. The RBD of the generator is shown in Figure 9. The complete reliability model equation for the gearbox and the generator are shown in 1 and 2 respectively.

$$\text{RGearbox} = \text{Rshaft.RIMS Bearings.Rkey Ways.RHSS Bearing.Rgears} \ldots \quad (1)$$

$$\text{Rgenerator} = \text{Rwindings.Rbearings.Rrotor} \ldots \quad (2)$$

Where R= reliability

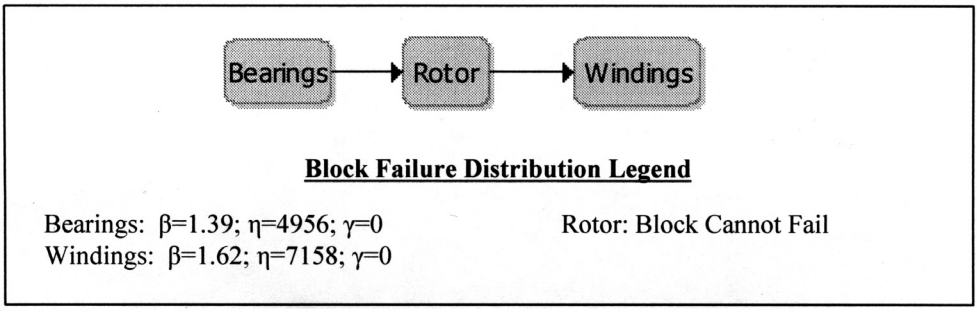


Figure 9. Reliability Block Diagram of a generator

The wind turbine's failure model is presented in Figure 10. The figure shows the RBD of key subsystems and their estimated values of β and η . The blades of the turbine are connected in *parallel* as they operate independently. However, all the blades must be in good operating condition before the wind turbine can function. This operating condition is depicted in the *3-out of-3* node (i.e. *3oo3*) in figure 10. A similar condition applies to the main bearings which require a *2-out of-2*. The operating condition of the mechanical and aerodynamic brakes are rather different, one of the brakes is enough to stop the turbine (i.e. *1-out of-2*). Safety requirements for the brakes demand a *2-out of-2* to avoid failures related to over-speeding of the turbine. These parallel arrangements are connected in series to the other subsystems of the wind turbine. The appropriate β and η values of each component and subsystem are incorporated in the model. The *start* and *end* blocks as well as the *connecting nodes* are set to *'block cannot fail'*. The turbines' complete reliability equation is presented in 3.

RTurbine = (REnd.RFlexible coupling.RGear box.RMain Shaft.RTower.RFoundation (RStart.R3oo3 (RBlade 2^3)) (R2oo2 (RBearing B^2)) (RGenerator.R2oo2 (RAerodynamic $brake^2$))) … (3)

Where:

R=Reliability; RBlade 1=RBlade 2=RBlade 3; RBearing B=RBearing A; RAerodynamic brake=RMechanical brake.

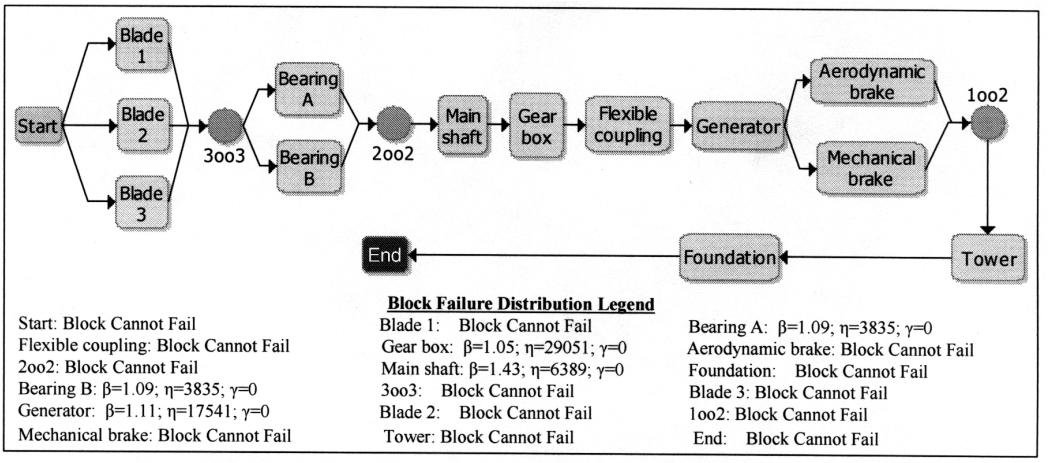


Figure 10. Reliability Block Diagram of a 600 kW Wind Turbine

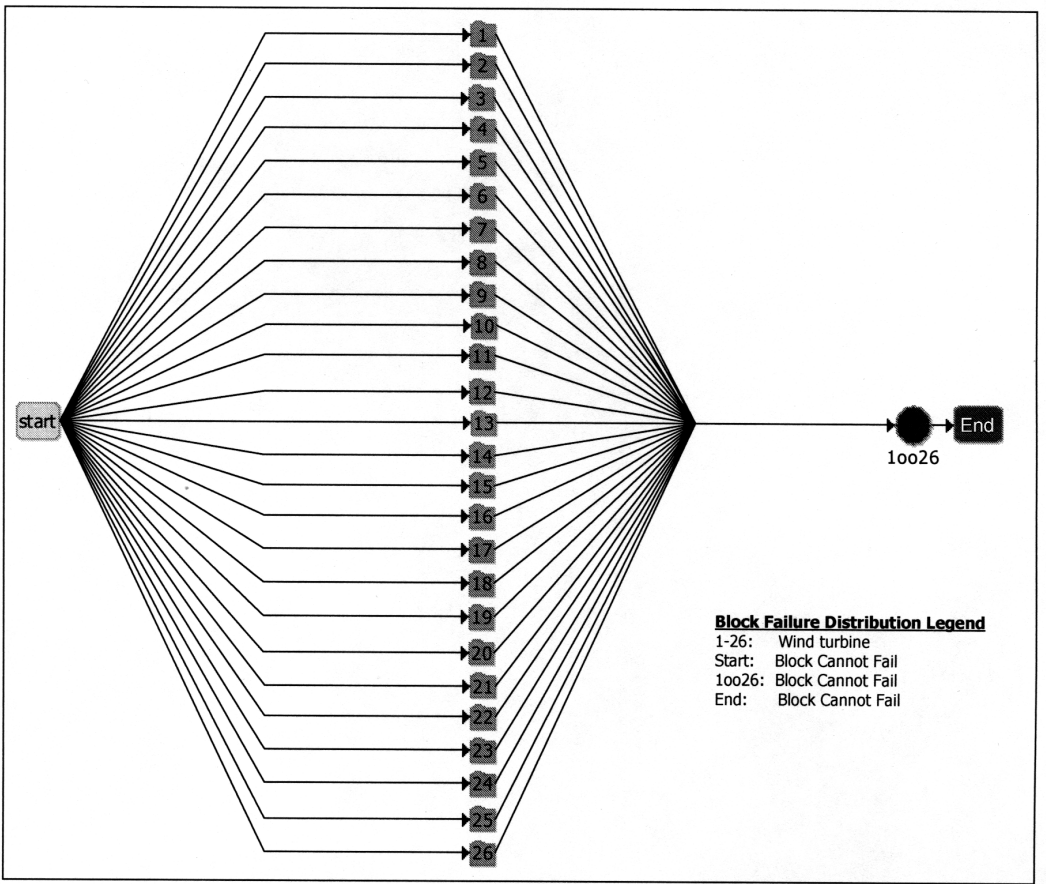


Figure 11 Reliability Block Diagram of a 26 x 600 kW wind farm

The failure model of the 26 x 600 kW wind farm is presented in Figure 11. Each of the 26 turbines in the figure is a replica of the 600 kW wind turbine failure model shown in figure 10. The turbines are connected in *parallel* since they operate independently in the wind farm.

3.2.6 Wind Turbine Model Assessment

The reliability, availability and maintainability (RAM) of the wind turbine is assessed over a period of 4 years; taking into account the costs and availability of maintenance crew and spares holding. The spare pool policy (Table 8) and the maintenance crew policies (Table 9 and 10) are incorporated into the model of the wind turbine.

The model is simulated 1000 times using the ReliaSoft BlockSim 7 on an annual basis over a period of four years (i.e. 1460 days). The turbine and its subsystems' up/downtime trend are shown in Figure 12. The subsystems uptime is relatively consistent over the period, given the defined maintenance strategy, crew and spare pool availability. The overview result is shown in Table 11 and the cost summary in Table 12. It is worth noting that the values given in tables 11-16 are cumulative. The mean availability (all events) of the wind turbine in the first is about 99.85%, this decreased to about 99.85% in the fourth year. The total down time increases from about 0.542 days in the first year to about 2.364 days in the fourth year. The total costs increase from £4,821.71 in the first year to about £19,889.80 in the fourth year. The break down of the total cost is shown in table 12.

3.2.7 Wind Farm Model Assessment

Given the reliability, availability and maintainability of the 600 kW wind turbine, the RAM of the 26 x 600 kW wind farm is assessed. The wind farm's up/downtime trend is shown in Figure 13. At 171.003 days, some wind turbines failed which brought the wind farm into a non-full operating time for 8.997 days. The non-full operating time is as a result of repairs or delays

Table 11. Wind Turbine Overview result

System Overview	Year 1	Year 2	Year 3	Year 4
General				
Mean Availability (All Events):	0.9985	0.9984	0.9984	0.9984
Std Deviation (Mean Availability):	0.0026	0.0021	0.0017	0.0015
Mean Availability (w/o PM & Inspection):	0.999	0.9989	0.9989	0.9988
Point Availability (All Events):	0.997	0.997	0.999	1
Reliability:	0.83	0.704	0.583	0.466
Expected Number of Failures:	0.177	0.337	0.537	0.731
Std Deviation (Number of Failures):	0.4023	0.5601	0.7329	0.841
MTTFF:	1978.6703	2097.2512	2050.662	1946.7559
System Uptime/Downtime				
Uptime:	364.4578	728.8623	1093.2533	1457.6361
Corrective Maintenance (CM) Downtime:	0.3765	0.8059	1.2492	1.7008
Inspection Downtime:	0.1657	0.3318	0.4974	0.6631
Preventive Maintenance (PM) Downtime:	0	0	0	0
Total Downtime:	0.5422	1.1377	1.7467	2.3639
System Downing Events				
Number of Failures:	0.175	0.334	0.531	0.72
Number of CMs:	0.175	0.334	0.531	0.72
Number of Inspections:	1.996	3.998	5.993	7.989
Number of PMs:	0	0	0	0
Total Events:	2.171	4.332	6.524	8.709
Costs				
Total Costs:	4,821.71	9,399.15	14,848.13	19,889.80

waiting for maintenance crew/spare-parts. In this case, the maintenance crew can only perform one task at a time, hence resulting in the long delays. Similar non-full operating time is recorded at 203.005, 365, 440.132 days, etc.

The overview result of the wind farm after the model is simulated 1000 times on annual basis over a period of 4 years is presented in Table 13, the cost summary in Table 14, crew costs summary in Table 15, and spare pool cost summary in Table 16. The mean availability *A (t)* of the farm at the end of the first year is 97.09%, this reduce to 96.77% in the fourth year. The reliability of the wind farm in the first is 0.01, this deteriorated to 0 in the fourth year. The

Table 12. Wind Turbine Cost Summary

System Cost Summary	Year 1	Year 2	Year 3	Year 4
Misc. Corrective Costs:	0	0	0	0
Costs for Parts (CM):	2,339.34	4,505.83	7,440.67	10,012.57
Costs for Crews (CM):	596.33	1,142.49	1,814.76	2,461.04
Total CM Costs:	2,935.67	5,648.33	9,255.44	12,473.61
Misc. Preventive Costs:	0	0	0	0
Costs for Parts (PM):	0	0	0	0
Costs for Crews (PM):	0	0	0	0
Total PM Costs:	0	0	0	0
Misc. Inspection Costs:	0	0	0	0
Costs for Crews (IN):	985.63	1,971.88	2,957.26	3,943.01
Total Inspection Costs:	985.63	1,971.88	2,957.26	3,943.01
Indirect Pool Costs:	900.41	1,778.95	2,635.44	3,473.18
Total Costs:	4,821.71	9,399.15	14,848.13	19,889.80

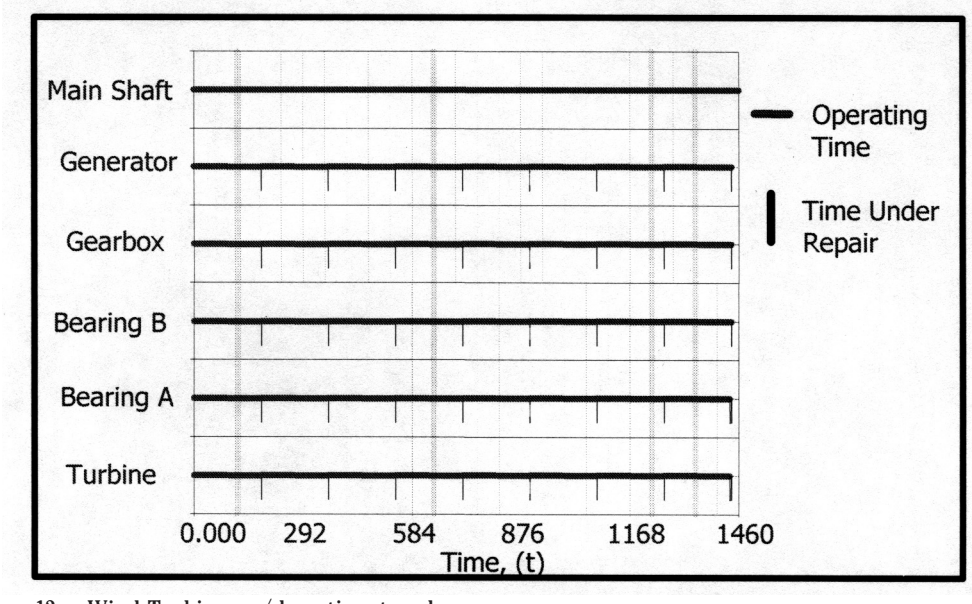


Figure 12 Wind Turbine up/downtime trend

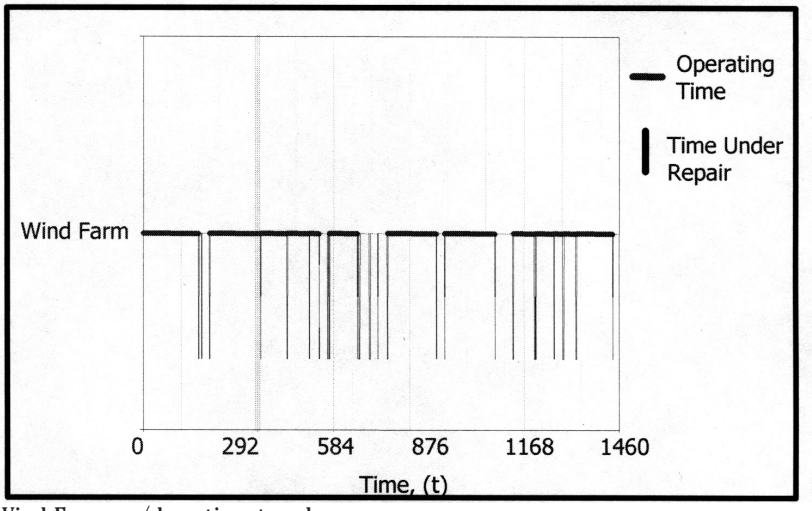


Figure 13 Wind Farm up/downtime trend

cumulative mean time to functional failure (MTTFF) decreases from 84.14 days in the first year to 83.22 days in the 4th year. The total down time of the wind farm over the period of 4 years is 47.11 days. The expected number of failures resulting in downing of the wind farm increases from 4.64 events in the first year to 19.71 events in the 4th year. The total cost of managing the farm as the result of the defined maintenance strategies is £105,541.35 at the end of the first year, and £436,949.67 at the end of the 4th year. The *spare pool costs* (i.e. overall costs of keeping the spares in the pool) are added to the total corrective maintenance (CM) costs and inspection costs to obtain the total costs of the strategies in each year (see table 14).

Table 13. Wind Farm Overview Result

System Overview	Year 1	Year 2	Year 3	Year 4
General				
Mean Availability (All Events):	0.9709	0.9701	0.9688	0.9677
Std Deviation (Mean Availability):	0.0149	0.0106	0.0088	0.0077
Mean Availability (w/o PM & Inspection):	0.9713	0.9705	0.9692	0.9682
Point Availability (All Events):	0.979	0.971	0.97	0.967
Reliability:	0.009	0	0	0
Expected Number of Failures:	4.644	9.391	14.551	19.712
Std Deviation (Number of Failures):	2.1274	2.93	3.689	4.2988
MTTFF:	84.1374	87.7502	79.713	83.2224
System Uptime/Downtime				
Uptime:	354.3634	708.1564	1060.8313	1412.891
CM Downtime:	10.4761	21.5224	33.6852	46.467
Inspection Downtime:	0.1605	0.3213	0.4835	0.642
PM Downtime:	0	0	0	0
Total Downtime:	10.6366	21.8436	34.1687	47.109
System Downing Events				
Number of Failures:	4.557	9.223	14.278	19.348
Number of CMs:	4.557	9.223	14.278	19.348
Number of Inspections:	1.934	3.873	5.829	7.737
Number of PMs:	0	0	0	0
Total Events:	6.491	13.096	20.107	27.085
Costs				
Total Costs:	105,541.35	213,517.63	323,608.40	436,949.67

Table 14. Wind Farm Cost summary

System Cost Summary	Year 1	Year 2	Year 3	Year 4
Misc. Corrective Costs:	0	0	0	0
Costs for Parts (CM):	63,567.66	129,282.31	195,818.84	265,566.00
Costs for Crews (CM):	15,561.91	31,512.02	48,801.66	66,171.75
Total CM Costs:	79,129.56	160,794.33	244,620.49	331,737.75
Misc. Preventive Costs:	0.000	0.000	0.000	0.000
Costs for Parts (PM):	0.000	0.000	0.000	0.000
Costs for Crews (PM):	0.000	0.000	0.000	0.000
Total PM Costs:	0.000	0.000	0.000	0.000
Misc. Inspection Costs:	0.000	0.000	0.000	0.000
Costs for Crews (IN):	25,629.61	51,260.08	76,891.29	102,518.18
Total Inspection Costs:	25,629.61	51,260.08	76,891.29	102,518.18
Indirect Pool Costs:	782.19	1,463.22	2,096.62	2,693.74
Total Costs:	105,541.35	213,517.63	323,608.40	436,949.67

Table 15. Wind Farm Crew summary

Period	Crew Policy	Calls	Accepted	Rejected	Time Used	Cost
	Crew A	4.557	4.557	0	10.4761	15,561.91
Year 1	Crew B	207.948	207.948	0	13.5169	25,629.61
	Crew A	9.223	9.223	0	21.5224	31,512.02
Year 2	Crew B	415.903	415.903	0	27.0344	51,260.08
	Crew A	14.278	14.278	0	33.6852	48,801.66
Year 3	Crew B	623.864	623.864	0	40.5521	76,891.29
	Crew A	19.348	19.348	0	46.467	66,171.75
Year 4	Crew B	831.79	831.79	0	54.0676	102,518.18

Table 15 shows the maintenance crew summary; crew A and B carry out corrective maintenance and inspections respectively. The number of calls made to the crews in each year, the accepted and rejected calls, the time used to inspect and repair the failures as well as the total costs of the crews is presented in the table. For example, a total of 4.557 and 19.348 calls were made to crew A in the 1st and the 4th year. A total of 10.476 and 46.467 days were used to attend to the calls at the cost of £15,561.91 and £66,171.75 respectively.

The summary of the spare parts re-supplied to the pools of each subsystem consumed are shown in Table 16. *Average Stock Level* (ASL) for each of the subsystems are indicated in column 3 of the table, and *item dispensed* in column 4. For example, 4 main bearings were dispensed to carry out repairs in the first year. The ASL in spare pool of bearings after the first year is 3 and the total cost is about £64,349.84.

4. CONCLUSION AND FUTURE WORK

This paper has used a quantitative approach to maintenance optimisation known as the *Modelling System Failures* to assess the failure characteristics of a 600 kW wind turbine and to optimise the maintenance activities of a 26 x 600 kW wind farm. Life-failure data of the 600 kW wind turbine have been collated from collaborating wind farm operators. The data have been analysed using Maximum Likelihood Estimation in the Weibull distribution. The β and η

Tables 16 Wind Farm Spare Pool Summary

Period	Pool	Average Stock Level (ASL)	Items Dispensed	Cost Per Item	Total Cost	Total Cost
	Spare Pool gearbox	0.8986	0.251	62,051.18	15,574.85	
	Spare Pool Shaft	1.8448	0.433	11,566.40	5,008.25	
Year 1	Spare Pool Bearings	3.0666	3.647	9,936.54	36,238.55	
	Spare Pool Generator	1.8792	0.313	24,051.74	7,528.20	64,349.84
	Spare Pool gearbox	0.8214	0.522	62,007.13	32,367.72	
	Spare Pool Shaft	1.7102	1.089	11,452.51	12,471.78	
Year 2	Spare Pool Bearings	2.8596	7.168	9,932.17	71,193.77	
	Spare Pool Generator	1.8008	0.612	24,039.65	14,712.26	130,745.53
	Spare Pool gearbox	0.7745	0.733	62,009.44	45,452.92	
	Spare Pool Shaft	1.5908	1.999	11,375.86	22,740.34	
Year 3	Spare Pool Bearings	2.758	10.942	9,927.92	108,631.33	
	Spare Pool Generator	1.7469	0.877	24,048.88	21,090.87	197,915.46
	Spare Pool gearbox	0.729	0.975	61,991.24	60,441.46	
	Spare Pool Shaft	1.4997	2.965	11,338.82	33,619.60	
Year 4	Spare Pool Bearings	2.7071	14.518	9,926.87	144,118.36	
	Spare Pool Generator	1.6842	1.254	23,987.50	30,080.32	268,259.74

parameters of the critical components and subsystems of the wind turbine were estimated using the ReliaSoft Weibull ++7. The estimates revealed that Condition-based maintenance strategy is the most suitable strategy to maintain the main-bearing, gearbox and the generator of the wind turbine while time-based is the appropriate strategy to maintain the main shaft. The estimated values of the β and η were used to design Reliability Block Diagrams to model the failures of the wind turbine and the wind farm. The reliability, availability and maintainability of the wind turbine and the farm were assessed using ReliaSoft BlockSim 7. In the assessment, the wind turbine and the farm models were simulated 1000 times over a period of 4 years; taking into account the cost and availability of maintenance crew and spare-holding of the critical components. The total costs of the regimes in the first and the fourth year are £105,541.35 and £436,949.67 respectively. A very significant part of the total costs was found to be the corrective maintenance.

Further research work is being undertaken to collate field failure data of the other components and subsystems of the wind turbine which are not included in the analysis reported in this paper. These will be assessed and included in the models. The reliability of the wind farm will be optimised further to meet a minimum threshold of 0.95, an ambitious and desired target of the collaborating wind farm operators. The spare pool policies will be optimised to reduce the total costs of spares over the period under consideration.

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