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Equipments Maintainability Using Simulation

By Ajide,O.O. , Adegbola,A.A

Ladoke Akintola University of Technology Ogbomosho, Nigeria

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Ajide,O.O.^α , Adegbola,A.A.^Ω

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1. INTRODUCTION

Maintainability is an important product characteristic and is also a design parameter (Hao, 2002). Maintainability deals with duration of maintenance outages or how long it takes to achieve with ease and speed the maintenance action compared to a datum. Maintainability is a characteristic of design and installation which is expressed as the probability that an item will be restored to specified condition within a given period of time when maintenance action is performed in accordance with prescribed procedures and resources (David, 2001). Several studies have been done on the maintainability of equipment. *Blanchard et al (1995)* showed that the key feature of merit for maintainability is often the Mean Time To Repair (MTTR) and a limit for the maximum repair time. Quantitatively, it refers to the ease with which hardware or software is restored to a functioning state. Maintainability is usually expressed as in equation 1.

$$M(t) = 1 - \exp(-t / MTTR) \quad (1a)$$

$$M(t) = 1 - \exp(-\mu t) \quad (1b)$$

Where μ is a constant maintenance rate which is equal to the inverse of MTTR. Wannu and Gandhi (2002) explained how maintainability of mechanical

equipment based on tribology can be evaluated. The authors developed a model, which is in terms of tribo-maintainability index. This model provides a guide to the designer in enhancing the maintainability of a system. In maintainability test, Roger (1979) described the prediction and allocation techniques that can be used by system designers and planners to determine the maintainability requirements for a system. He concluded from his work that testing whether a system meets maintainability requirements requires a special test that is isolated from other developmental and operational tests.

Many researchers have applied simulation technique in their studies. Houshyar (2003) used simulation in automotive industry to study the impacts of preventive maintenance policy in executing the machinery builder's recommended preventive maintenance policy without adversely affecting the stipulated production quotas. A simulation model was produced that incorporated key characteristics of the actual system. Running the model, the system throughout under two main scenarios was simulated and statistics tests was carried out which indicated that performing the recommended yearly preventive maintenance program would not affect the production quota. Ceric (1990) used simulation to determine vehicle storage space requirements and transportation (performability-Based fleet sizing in a material handling system) *Sean et al (2002)* applied simulation-based methods to develop life cycle analysis in order to aid the department of defence in its management of aging weapon systems. These tools are being used by the US Army, for example to quantify time-dependent life-cycle costs and impacts resulting from proposed aircraft and engine sustainment decisions, specifically, recapitalization maintenance concepts. In a paper presentation, Mart (2000) presented a model and analysis done to predict enemy force closure. The simulation replaces a pencil and ruler method that has been used by Department of defence planners for over a century. Jack (2001) used simulation software to simplify and speed up routine maintenance tasks for the next generation joint strike fighter (JSF).

The use of Monte Carlo in simulation is unique. SAFTAC is a Monte Carlo fault tree simulation program that provides a systematic approach for analyzing system, design, performing trade off studies and optimizing system changes (Crosetti, 1971). A combination of Monte Carlo - based Reliability, Availability and Maintainability simulation tools and electronic spreadsheets has been used in the life cycles

^{Author^α} : Department of Mechanical Engineering, University of Ibadan, Ibadan, Nigeria. E-mail : getjidefem2@yahoo.co.uk

^{Author^Ω} : Department of Mechanical Engineering, Ladoko Akintola University of Technology Ogbomoso, Nigeria.
E-mail : 080yinkus@yahoo.com

cost analysis of nuclear plant. Monte Carlo simulation has also been used in transportation system. If a simulation method could be developed that can generate a rare event mishap data in lieu of testing prototypes in actual operational environments, the statistical basis for predicting the system risk would exist. The Axiomatic Safety – Critical Assessment Process, ASCAP is such a simulation methodology (Kaufman and Giras, 2000).

This paper seeks to determine the ease of maintainability of imported “Tokunbo”¹ gear drives in power transmission, compare the maintainability of similar gear drives system manufactured by different companies and determine their MTTR using simulation.

II. METHODOLOGY

Imported second hand (Tokunbo)¹ gear drives were obtained from two experienced repair technicians who repair and market fairly used gear drives in Nigeria. These gear drives were made by British (A), Japanese (B) and German (C) firms. Ten usual faults or failures of these gears were obtained from these repair technicians who have almost equal training, qualification and experience. They were then used independently to troubleshoot and correct failures in the randomly selected “Tokunbo”¹ gear drives. The time taken by each technician to rectify each failure was noted and recorded. Average time taken to repair each fault or failure by each of these technicians was calculated. The evaluated average time taken to repair each fault for the gear drives of the three sources were combined in a single table and subjected to the Analysis of Variance (ANOVA). The reason was to determine first whether the difference between the time to repair/correct is significant. After it has been determined that the difference between time to repair is very significant, more data were generated using Monte Carlo simulation method for gear drives manufactured by the three sources. The data obtained which represents ten (10) simulated faults and repaired by one hundred technicians were subjected to further analysis using the following models:

$$M_{ct} = \sum_{i=1}^N M_{cti} \quad (2)$$

$$MTTR = \frac{\sum_{i=1}^N M_{cti}}{N} = \frac{M_{ct}}{N} \quad (3)$$

$$\sigma = \sqrt{\frac{N \sum_{i=1}^N (M_{cti})^2 - \left(\sum_{i=1}^N M_{cti} \right)^2}{N(N-1)}} \quad (4)$$

$$ERT = \frac{MTTR}{\text{anti log}(1.50\sigma^2)} \quad (5)$$

For a log normal distribution

$$MTTR_G = M_p TR = \text{anti log} \left[\frac{\sum_{i=1}^N \log M_{cti}}{N} \right] \quad (6)$$

$$M_{\max} = \text{anti log}(\log MTTR_G + 1.645\sigma \log M_{cti}) \quad (7)$$

Where

$$\sigma \log M_{ct} = \sqrt{\frac{\sum_{i=1}^N (\log M_{cti})^2 - \left(\sum_{i=1}^N \log M_{cti} \right)^2 / N}{N-1}} \quad (8)$$

$$M(t) = 1 - \exp(4 / MTTR) \quad (9)$$

$$M(t) = 1 - \exp(-\mu t) \quad (10)$$

NOTATIONS

M_{ct}	: Corrective Maintenance Time
MTTR	: Mean Time to Repair
ERT	: Equipment Repair Time
MTTR _G	: Geometric Mean Time to Repair
M_{\max}	: Maximum Maintenance Time
M(t)	: Maintainability Factor or Probability of Maintenance
σ	: Standard deviation
T	: specified Time to Repair
SST	: Total Sum of Squares
SSB	: Sum of Squares between Samples
SSW	: Sum of squares within Samples
F	: Fisher's Test
μ	: Repair Rate
$M_p TR$: Median Time to Repair

III. RESULTS/ANALYSIS

The experimental results of tests carried out, Analysis of Variance, summary of Monte Carlo simulation results and other analysis carried out are shown in the following tables :

¹ Tokunbo in Yoruba language in Nigeria simply means “imported”

Table 1 : Time taken to repair faults in gear drives from source A

Fault Number	Nature of Fault	Time Taken to Repair (minutes)		Average Time Taken by a Technician to Repair
		Technician I	Technician II	
1	Noise	59	61	60
2	Vibration	73	73	73
3	Overheating	72	76	74
4	Fatigue	88	88	88
5	Plastic flow	81	87	84
6	Tooth breakage	98	90	94
7	Corrosive wear	50	58	54
8	Uneven wear	20	30	25
9	Abrasive wear	65	65	65
10	Scoring	79	71	75
TOTAL				692

Table 2 : Time taken to repair faults in gear drives from source B

Fault Number	Nature of Fault	Time Taken to Repair (minutes)		Average Time Taken by a Technician to Repair
		Technician I	Technician II	
1	Noise	35	31	33
2	Vibration	89	89	89
3	Overheating	120	124	122
4	Fatigue	102	106	104
5	Plastic flow	80	82	81
6	Tooth breakage	81	81	81
7	Corrosive wear	22	30	26
8	Uneven wear	15	13	14
9	Abrasive wear	30	30	30
10	Scoring	45	51	48
TOTAL				628

Table 3 : Time taken to repair faults in gear drives from source C

Fault Number	Nature of Fault	Time Taken to Repair (minutes)		Average Time Taken by a Technician to Repair
		Technician I	Technician II	
1	Noise	103	101	102
2	Vibration	120	132	126
3	Overheating	199	201	200
4	Fatigue	210	214	212
5	Plastic flow	182	190	186
6	Tooth breakage	240	246	243
7	Corrosive wear	150	148	149
8	Uneven wear	100	100	100
9	Abrasive wear	98	92	95
10	Scoring	22	18	20
TOTAL				1433

Table 4 : Average time taken to repair faults in gear drives from sources A, B and C

Fault Number	Nature of fault	A	B	C
1	Noise	60	33	102
2	Vibration	73	89	126
3	Overheating	74	122	200
4	Fatigue	88	104	212
5	Plastic flow	84	81	186
6	Tooth breakage	94	81	243
7	Corrosive wear	54	26	149
8	Uneven wear	25	14	100

9	Abrasive wear	65	30	95
10	Scoring	75	48	20
Total = $\sum m_{ct}$		692	628	1433
Mean (\bar{x})		69.2	62.8	143.3
Grand Mean ($\bar{\bar{x}}$) = $\frac{69.2 + 62.8 + 143.3}{3} = 91.8 \text{ minutes}$				

Table 5 : Total Sum of Square (SST)

Fault Number	Nature of fault	A	$(x_i - \bar{x})^2$	B	$(x_i - \bar{x})^2$	C	$(x_i - \bar{x})^2$
1	Noise	60	1011.24	33	3457.44	102	104.04
2	Vibration	73	353.44	89	7.84	126	1169.64
3	Overheating	74	316.84	122	912.04	200	11707.24
4	Fatigue	88	14.44	104	148.84	212	14448.04
5	Plastic flow	84	60.84	81	116.64	186	8873.64
6	Tooth breakage	94	4.84	81	116.64	243	22861.44
7	Corrosive wear	54	1428.84	26	4329.64	149	3271.84
8	Uneven wear	25	4462.24	14	6052.84	100	67.24
9	Abrasive wear	65	718.24	30	3819.24	95	10.24
10	Scoring	75	282.24	48	1918.44	20	5155.24
			8653.20		20879.60		67668.60
Totals sum of squares = SST = 8653.20 + 20879.60 + 67668.60 = 97201.40							

Table 6 : of Square Between Samples (SSB)

Fault Number	Nature of fault	A	$(\bar{x}_A - \bar{x})^2$	B	$(\bar{x}_B - \bar{x})^2$	C	$(\bar{x}_C - \bar{x})^2$
1	Noise	60	510.76	33	841	102	2652.25
2	Vibration	73	510.76	89	841	126	2652.25
3	Overheating	74	510.76	122	841	200	2652.25
4	Fatigue	88	510.76	104	841	212	2652.25
5	Plastic flow	84	510.76	81	841	186	2652.25
6	Tooth breakage	94	510.76	81	841	243	2652.25
7	Corrosive wear	54	510.76	26	841	149	2652.25
8	Uneven wear	25	510.76	14	841	100	2652.25
9	Abrasive wear	65	510.76	30	841	95	2652.25
10	Scoring	75	510.76	48	841	20	2652.25
			5107.60		8410		2652.250
Sum of squares between samples SSB = 5107.60 + 8410 + 26522.50 = 40040.10							

Table 7 : Sum of Square Within Samples (SSW)

Fault Number	Nature of fault	A	$(x_{iA} - \bar{x}_A)^2$	B	$(x_{iB} - \bar{x}_B)^2$	C	$(x_{iC} - \bar{x}_C)^2$
1	Noise	60	84.64	33	888.04	102	1705.69
2	Vibration	73	14.44	89	686.44	126	299.29
3	Overheating	74	23.04	122	3504.64	200	3214.89
4	Fatigue	88	353.44	104	1697.44	212	4719.69
5	Plastic flow	84	219.04	81	331.24	186	1823.29
6	Tooth breakage	94	615.04	81	331.24	243	9940.09
7	Corrosive wear	54	231.04	26	1354.24	149	32.49
8	Uneven wear	25	1953.64	14	2381.44	100	1874.89
9	Abrasive wear	65	17.64	30	1075.84	95	2332.89
10	Scoring	75	33.64	48	219.04	20	15202.89
			3545.60		12469.60		41146.10

Sum of squares within samples $SSW = 3545.60 + 12469.60 + 41146.10$ $= 57161.30$

Table 8 : Analysis of Variance (ANOVA)

Sources of Variation	Sum of Square	Degree of Freedom	Mean Square
Between samples	40040.10	2	20020.05
Within samples	57161.30	27	2117.09
Total	97201.40	29	

$$F = \frac{\text{Between Sample Variation}}{\text{Within Sample Variation}} = \frac{20020.05}{2117.09} = 9.46$$

Table value of F for $V_1 = V_2 = 27$ at 5% level of significance is 3.35. Since the calculated value of F is more than the one obtained from the table, it can be inferred that the difference between the time to repair, restore or correct failure in the gear drives from sources A, B and C is very significant. Hence there is great

difference in the MAINTAINABILITY of gear drives obtained from the three sources. It is therefore important to determine which of these sources has the least Repair or Correct time. More data were generated using Monte Carlo simulation method. The data obtained were subjected to further analysis.

Table 9 : Average time taken (minutes) data used for Monte Carlo Simulation

Fault Number	Nature of Fault	A	B	C
1	Noise	60	33	102
2	Vibration	73	89	126
3	Overheating	74	122	200
4	Fatigue	88	104	212
5	Plastic flow	84	81	186
6	Tooth breakage	94	81	243
7	Corrosive wear	54	26	149
8	Uneven wear	25	14	100
9	Abrasive wear	65	30	95
10	Scoring	75	48	20
INTERVAL		25-94	14-122	20-243

The summary of Monte Carlo simulation of 1000 corrective time by 100 technicians and 10 faults for gear drives of sources A, B and C is given in table 10

Table 10 : Monte Carlo Simulation Results Summary

Fault Number	Nature of Fault	Simulation of time taken in minutes for 100 technicians			Average corrective time in Minute by a technician (M_{ct})		
		A	B	C	A	B	C
1	Noise	6057.112	6739.729	13717.93	60.57	67.40	137.18
2	Vibration	6053.265	7035.493	12999.68	60.53	70.35	130.00
3	Overheating	5933.154	6945.334	11544.56	59.33	69.45	115.45
4	Fatigue	5942.722	6379.348	13875.86	59.43	63.79	138.76
5	Plastic flow	5960.289	6785.992	13440.11	59.60	67.86	134.40
6	Tooth breakage	6233.922	6801.318	12660.45	62.34	68.01	126.60
7	Corrosive wear	5867.79	6213.58	13767.84	58.68	62.14	137.68
8	Uneven wear	5785.665	6698.434	12755.07	57.86	66.98	127.55
9	Abrasive wear	6193.47	6773.705	13021.72	61.93	67.74	130.22
10	Scoring	5862.941	6822.502	13865.23	58.63	68.23	138.65
Total		59890.34	67195.44	131648.50	598.90	671.95	1316.49

The mathematical models in equations 2 to 10 were applied to the results of table 10 for the purpose of determining M_{ct} , MTTR, σ , ERT, MTTR_G, M_{max} and $M(t)$. The results obtained from the models are shown in table 11, 12, 13 and 14.

Table 11 : Demonstration-test data for gear drives from source A

Fault Number	Nature of fault	M_{ct}	$\text{Log } M_{cti}$	$(\text{Log } M_{cti})^2$	$(M_{cti})^2$
1	Noise	60.57	1.782	3.176	3668.72
2	Vibration	60.53	1.782	3.175	3663.88
3	Overheating	59.33	1.773	3.145	3520.05
4	Fatigue	59.43	1.774	3.147	3531.92
5	Plastic flow	59.60	1.775	1.151	3552.16
6	Tooth breakage	62.34	1.795	3.221	3886.28
7	Corrosive wear	58.68	1.768	3.128	3443.34
8	Uneven wear	57.86	1.762	3.106	3347.78
9	Abrasive wear	61.93	1.792	3.211	3835.32
10	Scoring	58.63	1.768	3.126	3437.48
Totals		598.90	17.771	31.586	35886.93

Table 12 : Demonstration-test data for gear drives from source B

Fault Number	Nature of fault	M_{ct}	$\text{Log } M_{cti}$	$(\text{Log } M_{cti})^2$	$(M_{cti})^2$
1	Noise	67.40	1.829	3.344	4542.76
2	Vibration	70.35	1.847	3.412	4949.12
3	Overheating	69.45	1.842	3.392	4823.30
4	Fatigue	63.79	1.805	3.257	4069.16
5	Plastic flow	67.86	1.832	3.355	4604.98
6	Tooth breakage	68.01	1.833	3.358	4625.36
7	Corrosive wear	62.14	1.793	3.216	3861.38
8	Uneven wear	66.98	1.826	3.334	4486.32
9	Abrasive wear	67.74	1.831	3.352	4588.71
10	Scoring	68.23	1.834	3.363	4655.33
Totals		671.95	18.272	33.383	45206.42

Table 13 : Demonstration-test data for gear drives from source B

Fault Number	Nature of fault	M_{ct}	$\text{Log } M_{cti}$	$(\text{Log } M_{cti})^2$	$(M_{cti})^2$
1	Noise	137.18	2.137	4.568	18818.35
2	Vibration	130.00	2.114	4.469	16900.00
3	Overheating	115.45	2.062	4.253	13328.70
4	Fatigue	138.76	2.142	4.589	19254.34
5	Plastic flow	134.40	2.128	4.530	18063.36
6	Tooth breakage	126.60	2.102	4.420	16027.56
7	Corrosive wear	137.68	2.139	4.575	18955.78
8	Uneven wear	127.55	2.106	4.433	16269.00
9	Abrasive wear	130.22	2.115	4.472	16957.25
10	Scoring	138.65	2.142	4.588	19223.82
Totals		1316.49	21.187	44.897	173798.16

Table 14 : Results Summary for Maintainability Parameters

Parameter \ Source	A	B	C
Mct	598.90	671.95	1316.49
MTTR	59.89	67.20	131.65
MpTR	1.45	2.47	7.33
ERT	0.237	0.802	0.00000049
MTTR _G	59.85	67.17	131.43
M_{max}	65.43	67.30	131.87
M(t)	0.7106	0.6671	0.4299
	71.06%	66.71%	42.99%

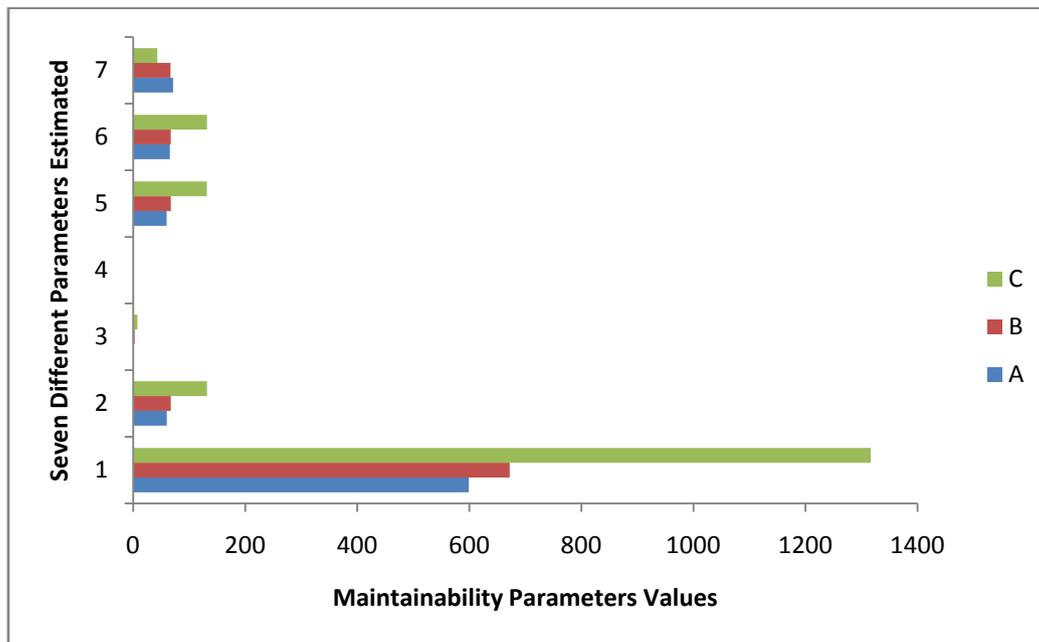


Fig.1 : Bar Charts Showing Summary Results for Different Maintainability Parameters (M_{ct} , MTTR, M_pTR , ERT, $MTTR_G$, M_{max} , $M(t)$)

Chart Key: The following numbers on the vertical axis represents the parameters indicated.

1- M_{ct} 2-MTTR, 3- M_pTR , 4-ERT, 5- $MTTR_G$, 6- M_{max} , 7- $M(t)$.

IV. DISCUSSIONS

As it can be observed at a glance from table 14 and figure 1, Results summary for maintainability parameters, the corrective time for A, B, and C are respectively 598.90 minutes, 671.95 minutes and 1316.49 minutes. It took the least time to correct failure in gear drives sourced in a firm from country A and the highest by a firm from country C. It is also observed that Mean Time To Repair (MTTR) and Geometric Mean Time To Repair ($MTTR_G$) of gear drives from the same source are approximately equal. It can be inferred from this that for a given source, MTTR of gear drives is a representation of its $MTTR_G$.

V. CONCLUSIONS

The results of this study have shown that gear drives from source A has the shortest maintenance time. It has the least MTTR, $MTTR_G$ and highest $M(t)$, probability of maintenance (maintenance factor). It is 71.06% maintainable. It can be deduced from this study that the same type of equipment manufactured from different sources have different maintainability. Therefore, before purchase, Maintenance Engineers who are responsible for the purchase of equipment, machine and system should ensure that their maintainability are considered or ascertained in order to ensure smooth production operations while in service.

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