Improving productivity of dragline through enhancement of reliability, inherent availability and maintainability

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Achieving the high production and productivity target is one of the biggest challenges for any mineral industry, in order to remain competitive in the global market. The maximum production of mining equipment is possible by ensuring maximum reliability and maintainability, which results in increasing the availability of equipment. The present paper is an endeavor to compute inherent availability of dragline machine and critically analyze reliability and maintainability of dragline's subsystems in one of the major open cast coal mines in India. The inherent availability of the studied dragline was 0.8402 (low). The Reliability, Availablity, and Maintainability (RAM) study has further highlighted the fact that the structural part with the maximum Mean Time To Repair (MTTR=88 h) and bucket subsystem with the minimum Mean Time To Failure (MTTF=54 h) are the major contributors to low inherent availability.

Key words: *Inherent Availability, Reliability, Maintainability, Dragline, Mining equipment, Open Cast Mine*

1. Introduction

Achieving high production and productivity target is one of the biggest challenges for any mineral industry, in order to remain competitive in the global market. The maximum production of mining equipment is possible by ensuring minimum shutdown and breakdowns to increase the availability of equipment. In other words, the rate of production is highly sensitive to the equipment availability (Rai 1999, Rai 2004, Osanloo 2006, Barabady 2007, Gupta and Bhattacharaya 2007, Dhillon 2008).

Various forms of availability are defined depending on its applicability and consideration of the time duration, such as operational availability and inherent availability.

1.1 Operational availability

Operational availability is associated with the operation of equipment or system. It can be represented by the total number of hours "within a period" that machinery is fit for work (Mirabediny 1998, Zoltan 1999, Jeong and Phillips 2001, Bhadury and Basu 2003, Rai et. al. 2011, Mohammadi et.al 2013, Mohammadi et. al. 2015). Mathematically, the operational availability can be expressed by Equations 1 or 2.

$$A_O = \frac{AT}{TT} \qquad (1) \quad or \quad A_O = \frac{AT}{POT} \qquad (2)$$

Where,

A_o is operational availability (calendar-time based or loading-time based),

AT is available time,

TT is total calendar time,

POT is planned operating time or loading time.

Figure 1 depicts the break-up of total calendar time (TT) of the equipment.

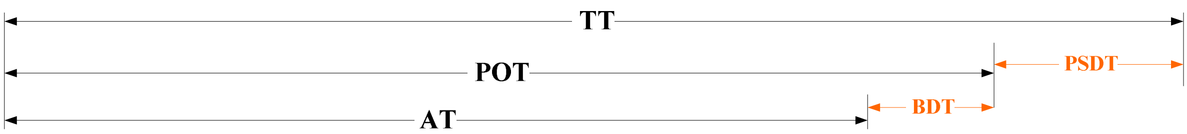

Fig. 1. The breakup of total calendar time of a component / equipment.

Where,

PSDT is planned shutdown time and

BDT is breakdown time.

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PSDT or non-scheduled time for the operation is the time during which equipment is planned for not to operate owing to administrative shutdown time, routine improvement and maintenance time. BDT is the period of time that equipment is non-operational as a result of maintenance due to any malfunction or breakdown. The maintenance program consists of planned and corrective maintenance.

1.2 Inherent availability

Inherent availability (A_i) is associated with the inbuilt characteristic of the equipment or its parts. It ignores the downtimes due to other sources which are not directly caused by the equipment design and are generally beyond the control of the designer. Hence, it is recommended to assess design characteristics during the design process that can be used as an important tool for framing preventive maintenance schedule, spare parts management and optimal replacement strategies (Kumar 1989, Sutton 1992, Ebeling 2000, Bhadury and Basu, 2003). Mathematically, the A_i may be expressed as:

$$A_i = \frac{MTTF}{MTTF + MTTR} \tag{3}$$

Where,

A_i is inherent availability,

MTTF is mean time to failure. It is the mean lifetime of an item and represents the average time elapsed after repairing the failed item to the occurrence of next failure. It excludes the idle time. And,

MTTR is mean time to repair. It represents the mean time required to repair a failed component and excludes other maintenance times such as waiting time.

From the above definition, it is clear that the inherent availability is a function of reliability parameter (how often a unit fails) and maintainability parameter (how fast the unit can be restored after a failure) (Dhillon and Singh 1981, Kumar 1988, Sutton 1992 and Dhillon 2008). Hence, the inherent availability (A_i) can be expressed as:

$$A_i = f\,(MTTF, MTTR) = f(R,M) \tag{4}$$

Where,

R is reliability characteristic of an item or system measured in terms of MTTF, and

M is maintainability characteristic of an item or system measured in terms of MTTR.

Hence, the studies of inherent availability include the analysis of reliability and maintainability. It is evident that if the reliability of a component or a system is poor, we can expect the occurrence of more failures. Reliability investigations are usually helpful in deciding the optimal maintenance intervals and the patterns of spare parts consumption. Therefore, one of the most effective ways of increasing equipment's inherent availability is to improve its reliability and maintainability, either by reducing the number of unplanned shutdowns or by minimizing the length of scheduled turnarounds (Kumar 1990 and Sutton 1992).

2. Research objectives

In this light, the present paper is an endeavor to critically analyze the inherent availability of biggest single-bucket excavator (the dragline machine) and identify the areas with low reliability and maintainability to indicate the bottleneck for potential improvement. Once the cause of failure is identified, its occurrence can be controlled either by eliminating these flaws during manufacturing or by suitable maintenance actions.

2.1. Case study

To accomplish the research objectives, field studies and field data acquisition were conducted in Northern Coalfields Limited (NCL) mines, Madhya Pradesh, India - one of the largest open cast coal field in the world. Geographically, the area lies between latitudes of 24° 0' to 24° 12' and longitudes 82° 30' to 82° 45'. The coalfield is currently operating nine fully mechanized opencast projects with an annual excavation capacity of 64 Mm^3 of overburden with Draglines (19 draglines), and 142 Mm^3 of overburden for shovel-dumpers combination (93 shovels and 534 dumpers), with the aim of producing almost 80 Mte of coal annually. The 24/96 dragline with a bucket capacity of 24 m^3 and boom length of 96 m was studied in the field to meet the objectives of the present research.

2.2. Research methodology

For the Reliability, Availability and Maintainability (RAM) analysis of dragline under study, the equipment was broken into seven major subsystems, connected in series and represented by a reliability block diagram as shown in Fig. 2. Bucket, ropes (drag and hoist ropes), motor generators (MG - set electrical parts), motor generators (MG - set mechanical parts), structure, other electrical parts and other mechanical parts represent the seven major subsystems of dragline under study.

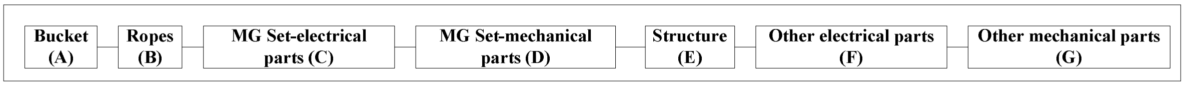

Fig. 2. A simplified reliability assessment block diagram of dragline subsystems.

Toward this, the frequency of breakdown, Time To Repair (TTR), Time To Failure (TTF) data was collected for various subsystems in chronological order from the maintenance record for a period of two years for subsequently performing the statistical analysis.

The framework for recording TTR and TTF is illustrated in Fig. 3. Fig. 3 depicts the break-up of Planned Operating Time (POT) and Time Between successive Failures (TBF) of any component or system/subsystem.

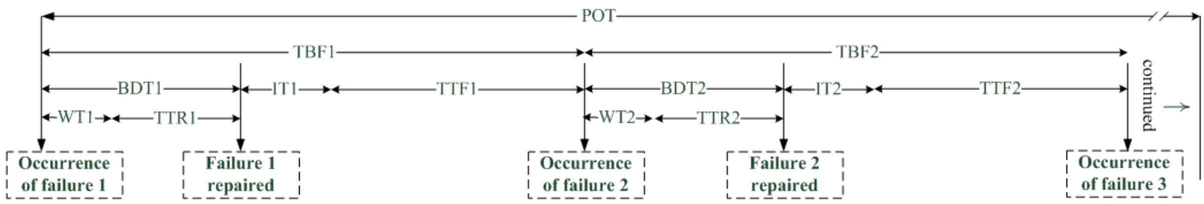

Fig. 3. The break-up of planned operating time of a component / subsystem.

Where,

BDT is breakdown time; it is the period of time that a piece of machinery or equipment is non-operational as a result of maintenance due to malfunction or breakdown.

WT is the waiting (delayed) time in repair and

IT is idle time. Idle time (IT) is considered the time for which the equipment is available and ready to operate but not involved in the production. These stoppages are not due to malfunctions or failures. Inordinate dozing, non-availability of power, poor blasting results, extended tiffin hours, time elapsed in shift changeovers, an extension of power cables, etc. are some of the reasons responsible for equipment idling.

Other acronyms are already defined.

To study the distribution of TTFs and TTRs, various probability models were tested as possible candidates. The most important steps in statistical analysis of data are the identification and use of the correct models for describing the TTFs and TTRs behavior of the equipment with time. Most of the statistical models are based on the assumption that the data are Independent and Identically Distributed (IID) and the system is “as good as new” after repair.

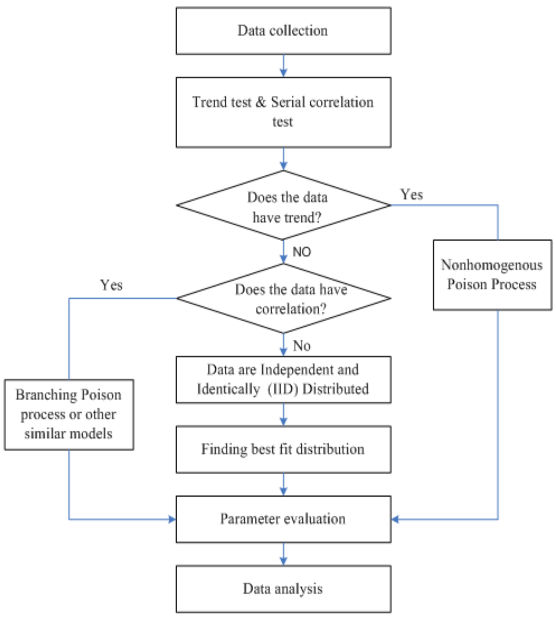

Fig. 4. The process of data analysis (adapted from Ascher and Feingold 1984).

Therefore, before modeling the data, it should be tested for the presence of serial correlation and the presence of a trend. If there is no trend and serial correlation, the assumption of the IID is true. So, renewal process techniques can be used for modeling. Once the data set exhibits the presence of a trend, it should be analyzed by non-stationary models such as the non-homogenous Poison process (based on power law process) model and not by the distribution method (Ascher and Feingold 1984, Kumar 1990, Rigdon and Basu 2000). The basic methodology for analyzing the data is illustrated in Fig. 4. The Kolmogorov-Smirnov (K-S) test was applied in selecting the best-fit distribution models. Data analysis was made by using MathWave Easy Fit 5.5 professional software.

3. Results and discussion

The data set was tested for the presence of serial correlation and trend. For example, to test the TTFs of the bucket for the presence of serial correlation, the x_{i-1} of data ((i-1)th value of TTFs), were plotted against the x_i of data (ith value of TTFs). The plot is shown in Fig. 5. The plotted points are randomly scattered without any pattern, and it can be interpreted that the TTFs of the bucket are free from serial correlation.
The data set was also tested for the presence of trend by plotting the cumulative time to successive failures (TTFs) against a cumulative number of failures. It was found that there are no structures or trend as interpreted from the linearity of the curves obtained (see Fig. 6).

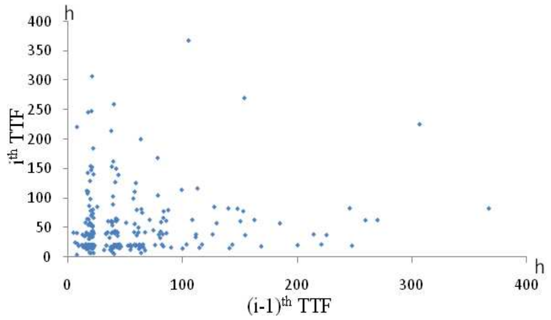

Fig. 5. Serial correlation test of TTFs data for a bucket.

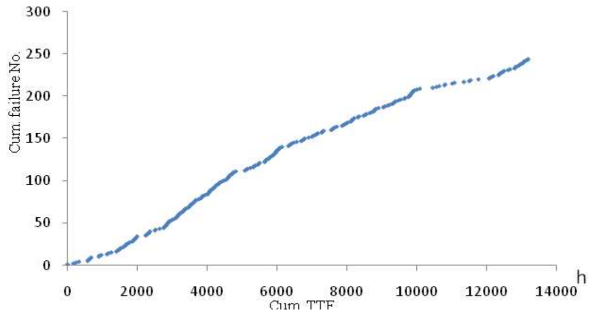

Fig. 6. The trend test for the TTFs data of bucket.

On similar lines, the assumption of the IID was tested for TTFs and TTRs of remaining six subsystems. The data sets were found to be free from the presence of trend and serial correlation. Hence, the assumption of the IID was not contradicted. So, the next step was to choose a best-fit probability distribution model using "goodness-of-fit" test to study the statistical characteristics of the data set. The result of statistical analysis for the TTF and TTR data of subsystems are summarized in Tables 1 and 2.

Tab. 1. Parameters of distributions for the TTFs data of subsystems.

Subsystem	**TTFs data**			**Parameters of distribution**			**Best fit**	**MTTF** [h]
	No.	**Min**[h]	**Max**[h]	**Exponential**	**Weibull**	**Lognormal**		
A	244	4.5	367.3	λ = 0.02, γ =4.5	α =1.4, β=55	σ=0.82, μ=3.6	Exponential	54
B	45	20	1500	λ = 0.00, γ =20	α =1.3, β=290	σ=0.94, μ=5.3	Weibull	270
C	12	32	3589	λ = 0.00, γ =32	α =0.83, β=570	σ=1.4, μ=6.0	lognormal	1100
D	7	59	3544	λ = 0.007, γ =58	α =0.55,β=1300	σ=1.5, μ=6.6	Exponential	1400
E	6	630	3000	λ = 0.0, γ =630	α =1.9, β=1700	σ=0.47, μ=7.3	lognormal	1700
F	36	7.5	1200	λ = 0.00, γ =7.5	α =0.81, β=350	σ=1.4, μ=5.2	Weibull	390
G	40	2	990	λ = 0.00, γ =2.0	α =0.65, β=260	σ =1.7, μ=4.8	Weibull	360

Tab. 2. Parameters of distributions for the TTRs data of subsystems.

Subsystem	**TTFs data**			**Parameters of distribution**			**Best fit**	**MTTR** [h]
	No.	**Min**[h]	**Max**[h]	**Lognormal**	**Exponential**	**Normal**		
A	244	0.2	11	σ =1.1, μ=0.17	λ = 0.53, γ =0.25	σ =2.4, μ=2.2	Lognormal	2.2
B	46	0.5	9.6	σ =0.8, μ=0.75	λ = 0.41, γ =0.5	σ =2.4, μ=3.0	Lognormal	2.9
C	13	1	48	σ =1.2, μ=2.2	λ = 0.06, γ =1.0	σ =17, μ=17	Lognormal	19
D	8	0.5	63	σ =1.9, μ=2.5	λ = 0.03, γ =0.5	σ =23, μ=31	Normal	31
E	7	2.8	400	σ =1.6, μ=3.2	λ = 0.01, γ =2.8	σ =150, μ=88	Lognormal	88
F	37	0.3	15	σ =1.1, μ=0.38	λ = 0.43,γ =0.3	σ =3.2, μ=2.6	Lognormal	2.7
G	39	0.3	56	σ =1.2, μ=1.5	λ = 0.12, γ =0.3	σ =12, μ=8.8	Lognormal	9.2

With the help of best-fit distribution of the data, the failure density function, reliability function, repairs time density function and maintainability graphs of all the dragline's subsystems with time were plotted as illustrated in Figures 7 to 20.

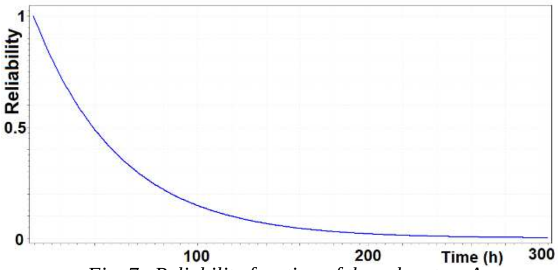

Fig. 7. Reliability function of the subsystem A.

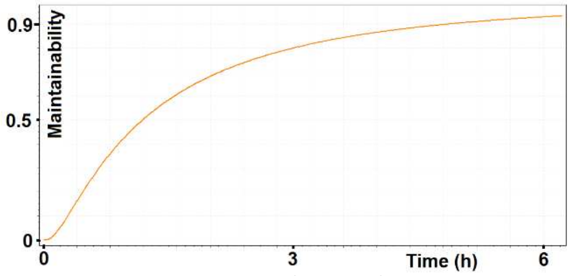

Fig. 8. Maintainability function of the subsystem A.

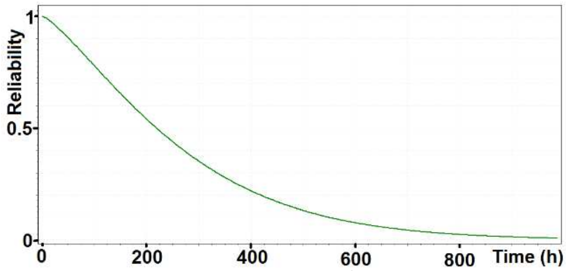

Fig. 9. Reliability Function of the subsystem B.

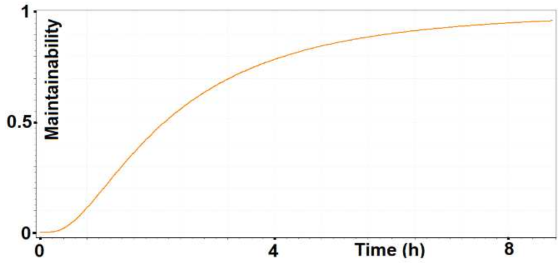

Fig. 10. Maintainability function of the subsystem B.

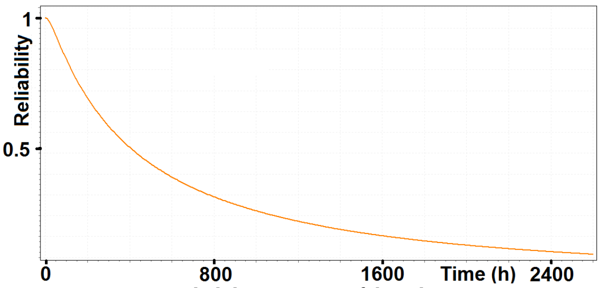

Fig. 11. Reliability Function of the subsystem C.

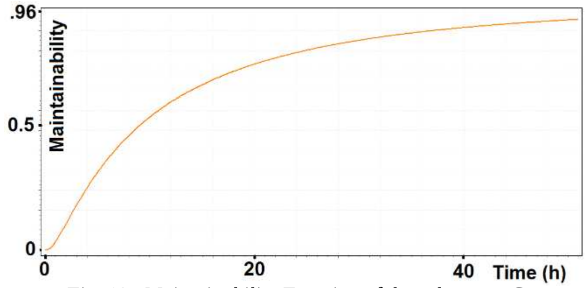

Fig. 12. Maintainability Function of the subsystem C

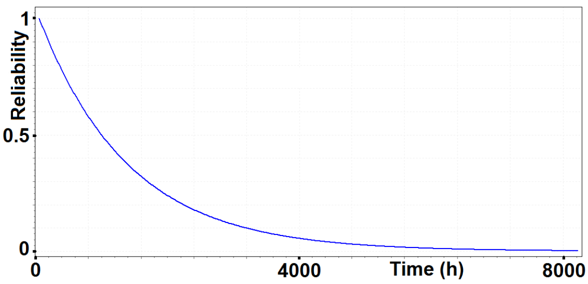

Fig. 13. Reliability Function of the Subsystem D.

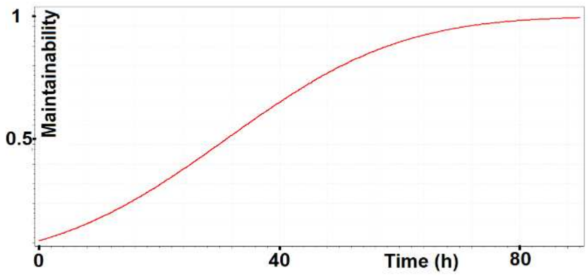

Fig. 14. Maintainability Function of the subsystem D.

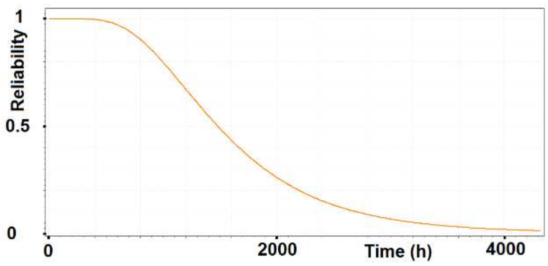

Fig. 15. Reliability Function of the subsystem E.

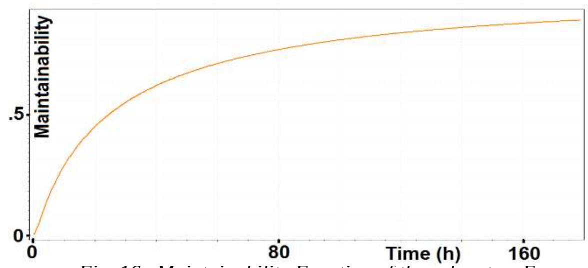

Fig. 16. Maintainability Function of the subsystem E.

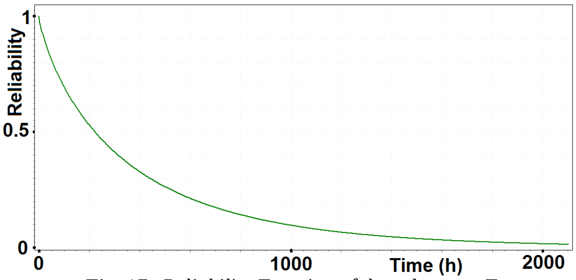

Fig. 17. Reliability Function of the subsystem F.

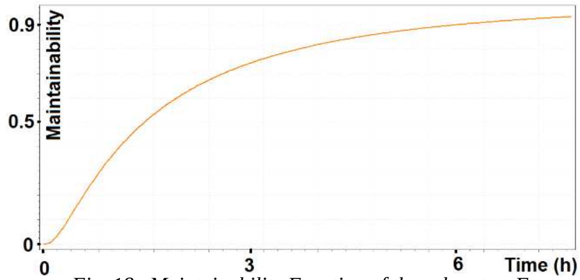

Fig. 18. Maintainability Function of the subsystem F.

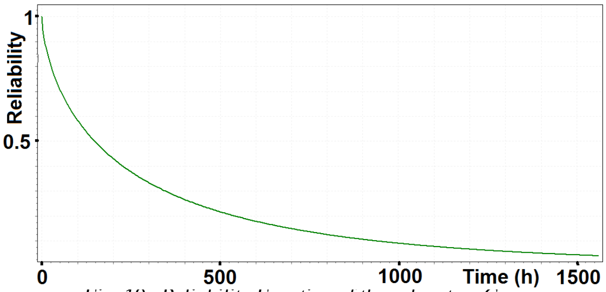

Fig. 19. Reliability Function of the subsystem G.

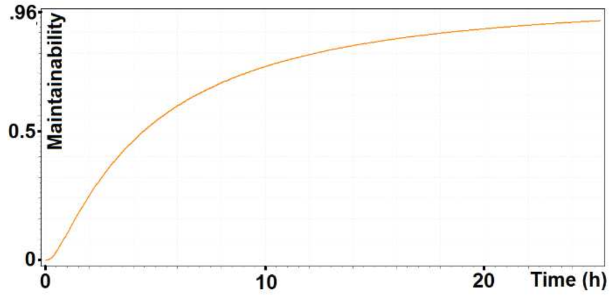

Fig. 20. Maintainability Function of the subsystem G.

From reliability figures, it is clear that the reliability of the bucket (subsystem A) is decreasing with time at a faster rate than all other subsystems, and it is the critical subsystem responsible for the poor reliability of dragline system. For a better understanding of this, the reliability figures of the dragline's subsystems at different times are summarized in Table 3.

Tab. 3. Reliability of dragline and its subsystems at different times.

Time [h]	Subsystems							system
	A	B	C	D	E	F	G	
	Reliability							
0	1	1	1	1	1	1	1	1.00
10	0.9	0.99	0.99	0.99	0.99	0.95	0.89	0.73
20	0.73	0.97	0.99	0.99	0.99	0.91	0.83	0.52
30	0.6	0.95	0.98	0.98	0.99	0.87	0.78	0.37
40	0.49	0.93	0.96	0.97	0.99	0.84	0.74	0.26
50	0.4	0.90	0.95	0.97	0.99	0.81	0.71	0.19
60	0.33	0.88	0.93	0.96	0.99	0.79	0.68	0.14
70	0.27	0.85	0.91	0.95	0.99	0.76	0.65	0.10
80	0.22	0.83	0.89	0.95	0.99	0.74	0.63	0.07
90	0.18	0.80	0.88	0.94	0.99	0.72	0.61	0.05
100	0.15	0.78	0.86	0.93	0.99	0.70	0.58	0.04
150	0.05	0.65	0.78	0.90	0.99	0.60	0.50	0.01
200	0.02	0.54	0.71	0.87	0.99	0.53	0.43	0.00
300	0.00	0.35	0.59	0.81	0.99	0.41	0.33	0.00

Based on Table 3, the reliability of bucket for 10 hours is 0.90 (R(10)=0.90), which means that the bucket will not fail for 10 hours of operation with only 90% probability. The analysis also shows that the reliability of the bucket approaches to zero after 300 hours of operation, meaning thereby that failure of the bucket is almost certain after 300 hours of its operation.

The structural part (subsystem E) is indicative of strong reliability in comparison with other subsystems. As Fig. 15 shows R(800) =0.90, which means that there is a 90 percent chance that structural part will not fail up to 800 hours of operation. The analysis also shows that the reliability of the structural part approach to zero after 5000 hours of operation, implying that the failure of the structure is almost certain only after 5000 hours of operation.

From maintainability graphs, it is clear that the bucket has better maintainability with time than other subsystems. Fig. 8 shows that maintainability of the bucket for 5 hours of repair time is 0.90. This means, there is a 90 percent chance, that any failure in the bucket will be repaired within 5 hours.

It is worthy to note that the structural subsystem suffers from poor maintainability. As Fig. 16 shows M(5)=0.17. This means, there is only 17 percent chance, that any failure in the structural part of dragline under study will be repaired within 5 hours.

As mentioned, the inherent availability is a function of reliability parameter (how often a unit fails) and maintainability parameter (how fast the unit can be restored after a failure). Tables 1 and 2 already provided the

MTTF and MTTR for subsystems of dragline under study. Therefore, inherent availability of the subsystem was computed by Equation 2 and the results are tabulated in Table 4. For instance, A_i for the bucket is computed by substituting the based values for MTTF and MTTR as 54 h and 2.2 h respectively in the Equation 2 as:

$$A_i = \frac{MTTF}{MTTF + MTTR} = \frac{54}{54 + 2.2} = 0.9609$$

Tab. 4. Rank of various dragline subsystems as per the values of MTTF, MTTR and A_i

Subsystem	MTTF [h]	MTTR [h]	A_i	Rank MTTF	Rank MTTR	Rank A_i
A	54	2.2	0.9609	7	1	6
B	270	2.9	0.9894	6	3	2
C	1100	19	0.9830	3	5	3
D	1400	31	0.9783	2	6	4
E	1700	88	0.9508	1	7	7
F	390	2.7	0.9931	4	2	1
G	360	9.2	0.9751	5	4	5

As all the subsystems are connected in series, hence the inherent availability of dragline system is:

$$(A_i)_s = \prod_{j=1}^{7} (A_i)_j \tag{4}$$

$$(A_i)_s = 0.9609 \times 0.9894 \times 0.9830 \times 0.9783 \times 0.9508 \times 0.9931 \times 0.9732 = 0.8402$$

Hence, the inherent availability of the given dragline is 0.8402 (low).

A scrutiny of inherent availability which results from Table 4 clearly indicates that the range of A_i for subsystems varies from 0.9508 to 0.9931. The ranking reveals that the inherent availability of other electrical parts (0.9931) is at the top and is followed by ropes (0.9894). The bucket and structural subsystems have the lowest inherent availability (0.9609 and 0.9508). The low range of A_i value for the structural subsystem is indicative of the poor maintainability (88 h MTTR) while this subsystem has maximum MTTF(1700 h). Bucket with minimum MTTR (better maintainability), suffers from low inherent availability due to the high frequency of breakdown (54 h MTTF).

It is suggested from the present study that special attention is required to improve the reliability of the bucket and maintainability of the structural part as these emerged as the critical subsystems. There is sufficient scope to improve the availability of dragline system by addressing to maintenance and repair issues for critical subsystems. So proper resource allocation (skill manpower, spare parts, etc.), a suitable maintenance policy and maintenance strategy may be followed to reduce the frequency of machine failure or abnormally high repair time to subsequently improve the dragline availability.

4. Conclusions

The major conclusions from this study are as follows:

- The RAM study has highlighted the fact that the structural part with maximum MTTR (88 h) and bucket subsystem with minimum MTTF (54 h) are the major contributors to the low inherent availability of dragline system and especial attention is required to improve maintainability of the structural part and reliability of the bucket.
- Study of successive time to failures and RAM analysis can provide a basis for framing preventive maintenance schedule, spare parts procurement and optimal replacement strategies.

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