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Performance evaluation of mining equipment in surface coal mine using reliability analysis

This article deals with reliability analysis of mining equipment such as shovels and dumper in a surface coal mine at The Singareni Collieries Co. Ltd., Telangana, by using the RBD and Markov model. First, the method is to obtain the MTBF and failure rate of the individual subsystem of a shovel and each dumper using RBD. Second, the attribute of the reliability-based Markov model is dissected. The method is shown to be an effective technique to obtain the reliability of the whole system of shovel and dumper during the working period. Then, the mathematical model has written to obtain the reliability of the whole system of the shovel and the dumper is described along with its validation. The outcome shows that the reliability with a time of the entire framework is the unwavering quality incorporated of subsystems and can be treated as a factor for the optimized process of availability of the same.

Keywords: *Reliability analysis, failure rate and MTBF*

1.0 Introduction

Currently, the mining industry needs more reliable modern mining equipment. The mining equipment in the industry process needs maintenance to avoid breakage. Several years ago, maintenance activities were commissioned only for repairs after problems due to the continuous failure of the mining equipment. Introducing the profitability of modern capital-intensive machines require the highest level of reliability and availability while working in the mine [2]. RAM (Reliability, availability and retention) of any machine is very important in recent years due to the competitive environment and its overhead costs/costs [2]. A reliability study of the machine is necessary to identify the improvements or modifications necessary to manage competitive pressures in the market.

The shovel-dumper system is intricate in design, exhaustive and has a bulky amount of elements. Therefore, there is an obvious need for reliable analysis based on the RBD and Markov model of such equipment used in the surface coal mine uses graphical and analytical techniques. Trend tests and correlation tests tested the time between the data failure (TBF) of the shovel-dumper and its subsystems. Also, two probability distribution functions are estimated, such as the Weibull distribution (1 parameter, 2 parameters and 3 parameters) and exponential distribution. Attempts have also been made to determine which distribution is best suited for the failure pattern of the shovel-dumper and its subsystems [1].

In the past research work, various procedures are utilized to investigate the conduct of the framework and to decide the unwavering reliability, availability and maintenance for various mining equipment. Probably the most normally utilized methods are fault trees, event tree analysis and reliable centralized maintenance. These methods will increase the performance of mining equipment in surface mines [4]. Reliability analysis was done on different systems, i.e., LHD, shovel, SDL, draglines, crushing plant, automotive manufacturing industry and railway manufacturing units. [2, 5-12]. These HEMM machines have several subsystems, and their productivity depends on every system. For example, dragline features a type of subsystem, like cubes, ropes, machinery, structural elements. The performance of the various subsystems of the traction system has been highly analyzed and it has been observed that it has a practical effect on the RAM of different subsystems [5]. The structural section of the dragline has a minimum time repair (t = 7665 hours or MTTR = 88 hours) [13-14] and the bucket subsystem has the least amount of time to fail (MTTF = 54 hours) [13]. Also, reliability was investigated on the drag line using Markov modelling for the 7665 working hours (t=7665 hours) [15].

Since reliability R(t) could be an attribute of the system that may achieve, it is needed to operate beneath a specified state for the declared interval of time. It shows by equation (1) and (2) [16-18].

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad \text{... (1)}$$

where, t time, γ location parameter, η scale parameter, β shape parameter,

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Therefore, failure rate

$$\lambda = \frac{\text{MTBF}}{\text{N}} \text{ and repair rate } \mu = \frac{\text{MTTR}}{\text{N}} \qquad (2)$$

The gradual deterioration of mechanical systems are appropriate to consider various states of the system or mechanical components to be considered rather than binary states for the availability analysis [19, 20]. Reliable engineering is the discipline to ensure that a system is reliable when it works a certain way. Classical reliability theory assumes that a component or system can be in one of the functional or non-functional states. However, engineering systems generally have several failed states in addition to the previously functioning states and the completely failed states. Especially in today's real-world problems, a large number of state systems must be considered, and the great need for accurate reliability assessment and better design makes it difficult to use binary trust techniques. Hence, multi-state reliability theory recognizes many possible states of the engineering system [21, 22].

Therefore, mining machines in surface mines is increasing in both size and complexity, and this requires high performance and reliability of the device [23]. The consequences of failure are many and varied [24]. Depending on the elements and stakeholders involved, almost all failures have an economic impact. Equipment or equipment failure not only results in a loss of productivity, but also results in a loss of service quality in a timely manner and can lead to safety and environmental issues that damage the company's reputation. Therefore, improving and improving the performance of the mining chain is more demanding and complex than ever. To improve the system it needs to be analyzed. The analysis one uses depends on the required output. Improving system performance means getting the maximum output the system can handle. However, there are costs to improve the system. Therefore, improvements should be made where profitability increases. Venkatesha, B K et al. [30-32] studied the mechanical properties of hybrid composites. Therefore, focusing on the reliability, storage and analysis available is essential to improving the performance of mining equipment by ensuring that it is available for production on a production schedule.

TABLE 1: FAILURE SUMMARY OF VARIOUS SUBSYSTEMS OF SHOVEL AND DUMPER

Subsystems of shovel	SS1	SS2	SS3	SS4	SS5	SS6	SS7	SS8	SS9	SS10	
S1	N	0	3	34	0	54	23	54	0	10	3
	MTBF	0	1581.25	193.47	0	111.90	281.24	164.94	0	601.05	1606.20
	λ	0	0.00	0.01	0	0.01	0.00	0.01	0	0.00	0.00
	MTTR	0	24.00	5.57	0	3.19	3.88	5.26	0	2.30	592.35
	μ	0	0.04	0.18	0	0.31	0.26	0.19	0	0.44	0.00
Subsystems of dumper	DS1	DS2	DS3	DS4	DS5	DS6	DS7	DS8	DS9	DS10	
D1	N	12.00	3.00	0	13.00	5.00	10.00	10.00	0	0	3.00
	MTBF	636.31	1611.20	0	538.75	482.86	351.26	881.59	0	0	1467.52
	λ	0.00	0.00	0	0.00	0.00	0.00	0.00	0	0	0.00
	MTTR	15.33	6.85	0	7.16	174.91	53.41	16.92	0	0	11.31
	μ	0.07	0.15	0	0.14	0.01	0.02	0.06	0	0	0.09
D2	N	8.00	4.00	0	11.00	4.00	9.00	6.00	0	0	4.00
	MTBF	684.66	527.67	0	529.16	943.87	577.13	554.27	0	0	921.69
	λ	0.00	0.00	0	0.00	0.00	0.00	0.00	0	0	0.00
	MTTR	8.69	6.30	0	24.35	6.58	55.19	96.56	0	0	8.80
	μ	0.12	0.16	0	0.04	0.15	0.02	0.01	0	0	0.11
D3	N	2.00	3.00	0	36.00	10.00	7.00	2.00	15.00	8.00	5.00
	MTBF	889.34	717.25	0	180.07	548.09	656.02	1372.41	341.51	882.43	733.36
	λ	0.00	0.00	0	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	MTTR	163.21	26.14	0	10.03	58.60	28.79	8.68	5.53	12.26	21.62
	μ	0.01	0.04	0	0.10	0.02	0.04	0.12	0.18	0.08	0.05
D4	N	0	7.00	0	34.00	28.00	11.00	2.00	7.00	2.00	4.00
	MTBF	0	957.66	0	233.89	292.74	392.52	595.04	1123.93	923.38	716.46
	λ	0	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	MTTR	0	103.39	0	7.90	15.41	21.96	8.42	6.29	0.88	12.29
	μ	0	0.01	0	0.13	0.07	0.05	0.12	0.16	1.14	0.08

2.0 Case study

Individual shovel and dumper were premeditated and significantly analysed with the help of failure data (TBF) and repair rate (TTR), which has tabulated in Table 1. These failure data was collected from the logbook of the machines record from the investigation site, i.e., The SCCL, Telangana (coal mine), about different subsystems of the shovel-dumper system. In Table 1, failure rate (l) and repair rate (m) of each subsystem of the shovel and dumper were calculated using Equation (1). During this case study, one shovel (S1) having capacity of 12 m^3, Komastu make and four dumpers (D1, D2, D3 and D4) are 100-tonne capacity which is made by BEML and Komastu were selected based on match factor, i.e., 1:4 of the mine and its production. Also, each shovel and dumper has categorized into 10 subsystems based on the collected failure data as mentioned in Table 2.

The major mechanical failures of the subsystem of a shovel are given in Fig.1.

a. Arm cylinder: The arm cylinder is attached to the boom and is driven by one or two hydraulic cylinders that are attached to the upper part of the boom. They are used for the horizontal movement.
b. Bucket: The excavation bucket is made up of hard steel and normally has teeth that come out of the cutting edge to break the hard rock and prevent wear of the container.
c. Hydraulic and electrical subsystems: An oil cooler is installed under the device, which improves the reliability of the hydraulic system during the sudden increase in temperature. In addition to the main filter, a 52 mm line filter is established at the inlet of the transmission control valve. This system helps prevent secondary errors.

Similarly, the mechanical failures of the subsystems taken in dumper are givein in Fig.2

a. Differential system: The differential is a device that separates the power between two wheels. When the car is driving, its wheels will travel the same distance and

TABLE 2: SUBSYSTEMS AND THIER FAILURE CODES

	Subsystems of shovel S1	Failure code	Subsystems of dumpers D1, D2, D3, D4	Failure code
1	Arm cylinder	SS1	Braking	DS1
2	Boom cylinder	SS2	Differential subsystem	DS2
3	Bucket	SS3	Drive trains	DS3
4	Cab and its attachment	SS4	Electrical subsystem	DS4
5	Electrical subsystem	SS5	Engine	DS5
6	Engine	SS6	HPSS	DS6
7	Hydraulic subsystem	SS7	Steering subsystem	DS7
8	Power train	SS8	Structural subsystem	DS8
9	Structure	SS9	Tires and rims	DS9
10	Undercarriage	SS10	Transmission subsystem	DS10

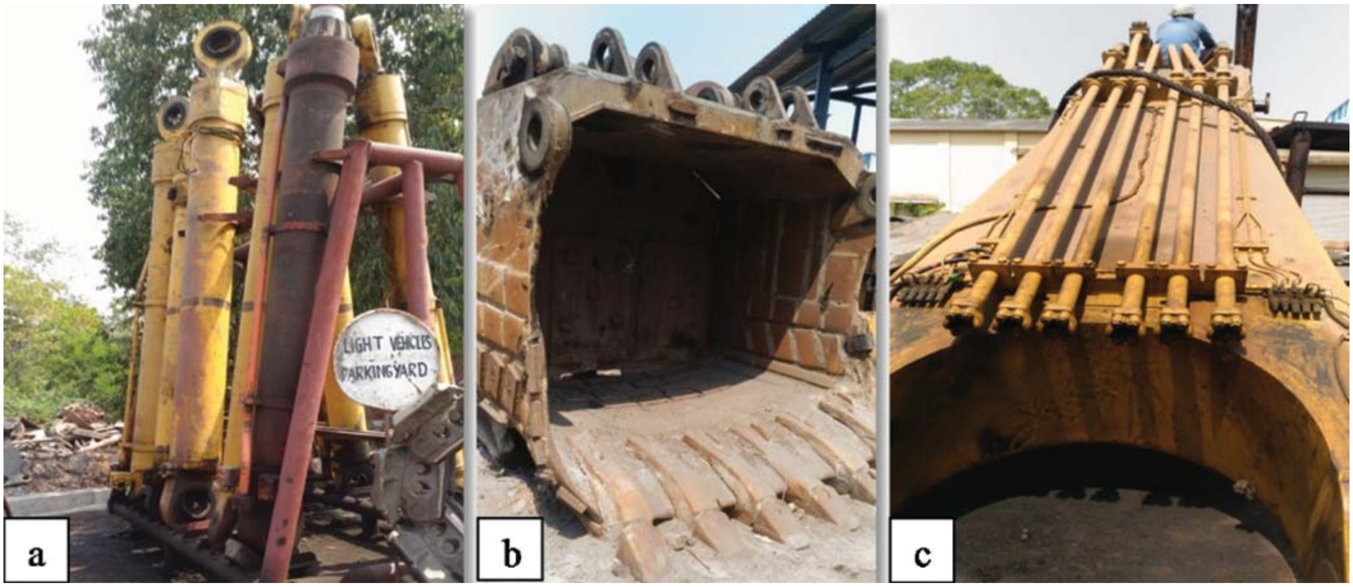

Fig.1: Major mechanical failure of subsystems of the shovel: a. Arm cylinder, b. Bucket, c. Hydraulic and electrical subsystems

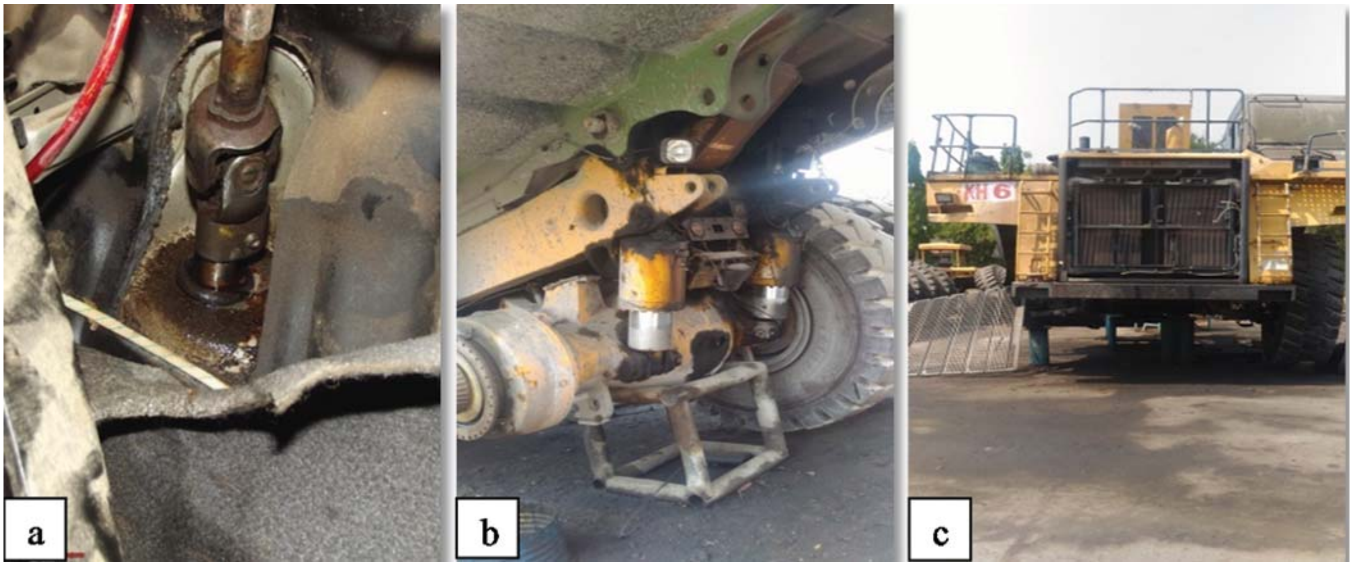

Fig.2: Major mechanical failures of subsystems of the dumper: a. Hydraulic subsystems, b. Hydropneumatic suspension subsystem, c. Engine subsystem

rotate at the same speed. The differential allows the wheel to rotate at both speeds. Most cars on the road have this type of differential.

b. Hydropneumatic suspension subsystem: Hydropneumatic suspensions system combines the fine properties of gas springs with the favourable damping properties of the hydraulic fluid. The advantages of these systems are particularly suitable for automotive applications such as trucks, trucks and agricultural equipment.

c. Engine subsytem: The engine is the most important part of any heavy earthmoving machinery (HEMM). It is the central processing unit of any HEMM that combines up all other components and products kinetic energy for running the HEMM.

3.0 Reliability block diagram

Both shovel and dumper divided into ten subsystems. Every subsystem is connected in series and the same has represented with the help of RBD. Figs. 3 and 4 show the RBD of the shovel (S1) and dumpers (D1, D2, D3 and D4), respectively. In each figure, there are 10 subsystems (SS1 to SS10 and DS1 to DS10) are connected in series. Therefore the overall reliability of the shovel will follow a mathematical model for S1 [Equation (3)]. In this, reliability prediction has carried out using Reliability Isograph workbench under the RWB module based on the failure rate of each subsystem of the shovel and dumper, which is tabulated in Table 3.

3.1 Formulation of mathematical model

For S1

$R_{S1}(t) =$

$$e^{-\left(\frac{t_{SS1}-\gamma 1}{\eta_{SS1}}\right)^{\beta_{SS1}}} + e^{-\left(\frac{t_{SS2}-\gamma_{SS2}}{\eta_{SS2}}\right)^{\beta_{SS2}}} + e^{-\left(\frac{t_{SS3}-\gamma_{SS3}}{\eta_{SS3}}\right)^{\beta_{SS3}}}$$

$$+ e^{-\left(\frac{t_{SS4}-\gamma_{SS4}}{\eta_{SS4}}\right)^{\beta_{SS4}}} + e^{-\left(\frac{t_{SS5}-\gamma_{SS5}}{\eta_{SS5}}\right)^{\beta_{SS5}}} + e^{-\left(\frac{t_{SS6}-\gamma_{SS6}}{\eta_{SS6}}\right)^{\beta_{SS6}}}$$

$$+ e^{-\left(\frac{t_{SS7}-\gamma_{SS7}}{\eta_{SS7}}\right)^{\beta_{SS7}}} + e^{-\left(\frac{t_{SS8}-\gamma_{SS8}}{\eta_{SS8}}\right)^{\beta_{SS8}}} + e^{-\left(\frac{t_{SS9}-\gamma_{SS9}}{\eta_{SS9}}\right)^{\beta_{SS9}}}$$

$$+ e^{-\left(\frac{t_{SS10}-\gamma_{SS10}}{\eta_{SS10}}\right)^{\beta_{SS10}}}$$

$$R_{S1}(t) = R_{SS1}(t) + R_{SS2}(t) + R_{SS3}(t) + R_{SS4}(t) + R_{SS5}(t) + R_{SS6}(t) + R_{SS7}(t) + R_{SS8}(t) + R_{SS9}(t) + R_{SS10}(t)$$

$$(\text{Since } R_{SS1}(t) = R_{SS4}(t) = R_{SS8}(t) = 1) \quad \ldots (3)$$

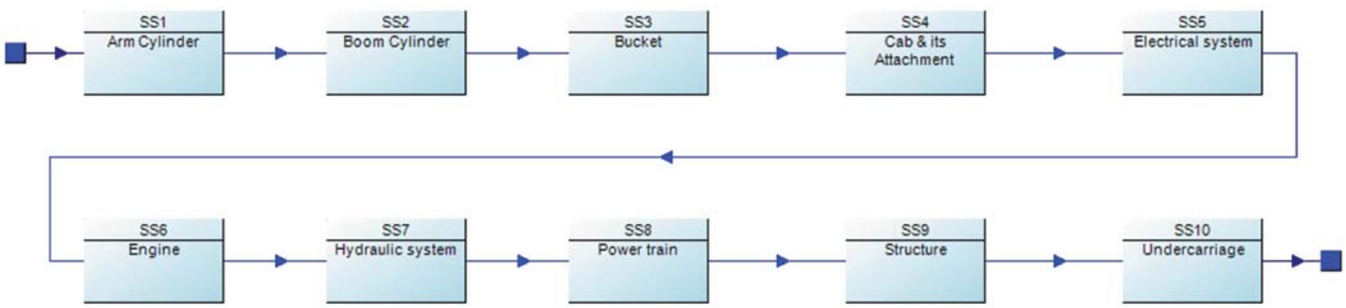

Fig.3: RBD of shovel S1

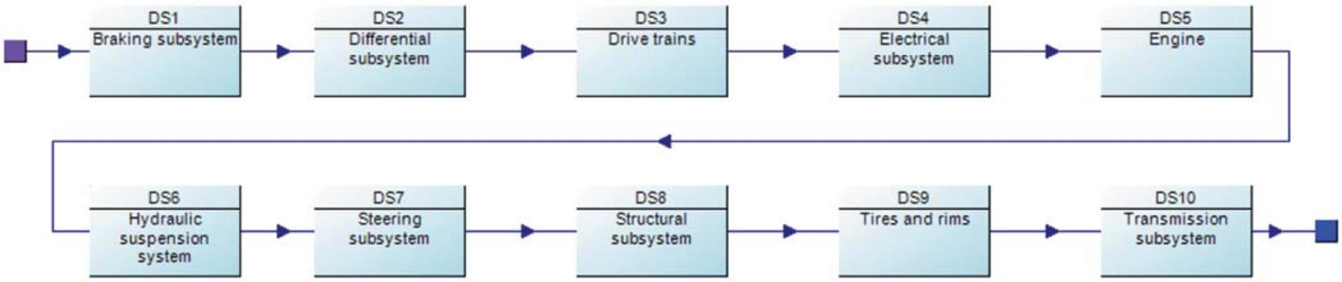

Fig.4: RBD of dumpers (D1, D2, D3, D4)

Table 3: Reliability and unreliability prediction of shovel and dumper using RBD

Systems	S1	D1	D2	D3	D4
MTBF in hrs	43.83	110.12	126.83	67.36	62.52
F(t) RBD	0.656	0.655	0.7499	0.6939	0.6331
R(t) RBD	0.344	0.345	0.25	0.306	0.367

Similarly, for dumpers (D1, D2, D3 and D4) will follow the same procedure.

4.0 Markov modelling

The Markov model is employed for the simulation method wherever the failure rate and repair rate square measure fastened. It is an influential method to find the R (t) of a repairable subsystem whose residence time follows the Weibull distribution [25].

Mathematically,

$$R(t,\ t + dt) = \sum_{Z_i \varepsilon \cup} P_{ij}\ (t)\ R_{sj}\,(dt),\ i = 0, 1, 2... m,\ dt > 0$$

$$R(dt)\ = \lim_{t \to \infty}\ R(t,\ t + dt) = \sum P_j(t)\ R(dt),\ \ dt\ > 0$$

With

$$P_j\ =\ \lim_{t \to \infty}\ P_j(t)\ =\ \lim_{t \to \infty} p_{ij}\,(t)$$

From

$$\rho_j P_j\ =\ \sum_{i=0, i \neq j}^{m} P_i \rho_{ij}\ \ i,\ j \in \{0,.....m\}$$

$$P_0\ +\ P_1\ +\ P_2 ....P_m\ = 1$$

where, R (t, t + dt) = P_r [system up in (t, t + dt), Z_i is entered at t = 0, $Z_i\ \varepsilon$ U (in general) R(dt)

= P_r [system up in (t, t + dt), in fixed state or for $t \to \infty = t \to \infty = \lim_{t \to 0} \frac{1}{dt} P_r$ {transition from Z_i to Z_j in (t, t+dt)

Step-by-step studies are needed to obtain the reliability and empirical analysis of the shovel-dumper system in surface coal mines. A reliable block diagram will help to understand all the components of the system. Some assumptions are measured to constitute a transition matrix for the analysis of the Markov chain analysis. The analysis of the stability results of the shovel-dumper system has performed for the determination of critical failures.

The subsystems of shovel and dumpers still exists in two state, they are in working state and failure state. When the system changes from a state that does not work (downstate) to a state that works (upstate), it shows that the repair is performed while the system changes from the working state (upstate) to inactive status (downstate). [26-29]. Detailed working conditions and non-working conditions are listed in Table 4.

Table 4: Relevance of ten components with eleven states

	State	State of subsystem	State system	Probability being state
1	0	No Failure	Working State (WS)	$P_0(t)$
2	1	SS1/DS1 Failed	Failure State (FS)	$P_1(t)$
3	2	SS2/DS2 Failed	Failure State (FS)	$P_2(t)$
4	3	SS3/DS3 Failed	Failure State (FS)	$P_3(t)$
5	4	SS4/DS4 Failed	Failure State (FS)	$P_4(t)$
6	5	SS5/DS5 Failed	Failure State (FS)	$P_5(t)$
7	6	SS6/DS6 Failed	Failure State (FS)	$P_6(t)$
8	7	SS7/DS7 Failed	Failure State (FS)	$P_7(t)$
9	8	SS8/DS8 Failed	Failure State (FS)	$P_8(t)$
10	9	SS9/DS9 Failed	Failure State (FS)	$P_9(t)$
11	10	SS10/DS10 Failed	Failure State (FS)	$P_{10}(t)$

4.1 Transition diagram and Markov modelling

In transition diagram, if all 10 subsystems are working properly, i.e., state WS (working state), so that system is in fully working condition. If one subsystem fails, the whole system will shut down because all subsystems are connected in series. For example, If SS1 failed and the other 9 subsystems will fail, it can be called as FS (Failed states), its whole results system (shovel either dumper will be incomplete failed conditions because all subsystems have connected in series. All possible working state and failure states of systems are tabulated in Table 4.

The transition diagram of S1, D1, D2, D3 and D4 has been shown in Figs.5, 6, 7, 8 and 9 were constructed based on RBD. The work state is defined as ‘0’, and the inactivity or failure state is defined as ‘i’ (i=1,2,3,4). When the machine (shovel and dumper) is started (for example, at t=0), the machine is in working condition and the subsystem is downstate and vice versa mentioned in Table 4. The changing situation describes only the up and down and vice versa. The subsystem is at the discretion and also in a continuous state.

Based on the above state transition diagrams, the Markov

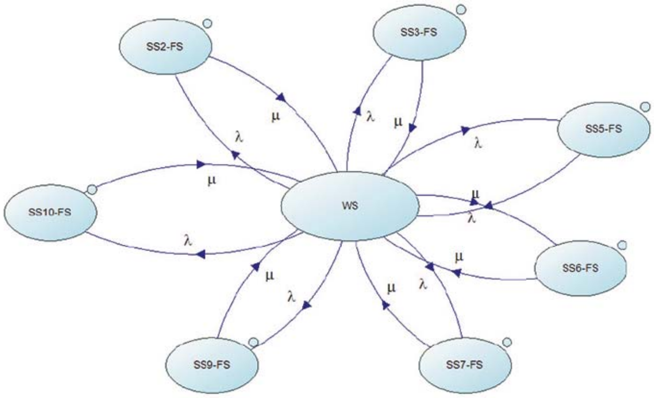

Fig.5: State diagram of S1

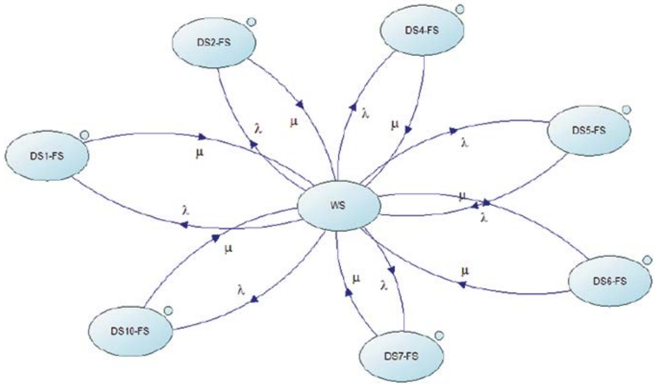

Fig.6: State diagram of D1

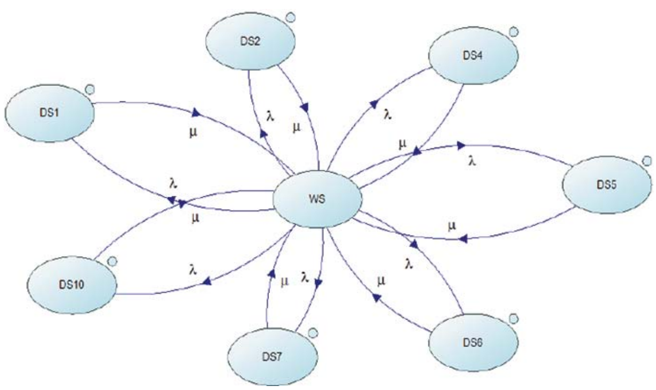

Fig.7: State diagram of D2

equation can be derived. Let $P_0(t)$ constitute the probability of 'working state' (0) in both shovel and dumper at time t. $P_i(t)$ (i.e., i=1, 2, 3,….) describes the probability of 'failure states (i) in subsystem at time t, where i=1,2,3,4…. The likelihood that the system is in the operative state when tiny measure (dt) is given by,

4.2 MARKOV EQUATION FOR SHOVEL S1 (Fig.3)

P_0 (t + dt) = [(Probability of working state at t) + [(Probability of being failed at time t)] is

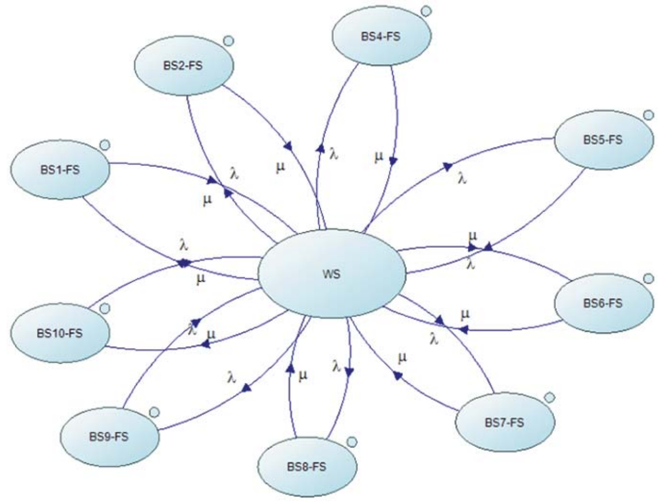

Fig.8: State diagram of D3

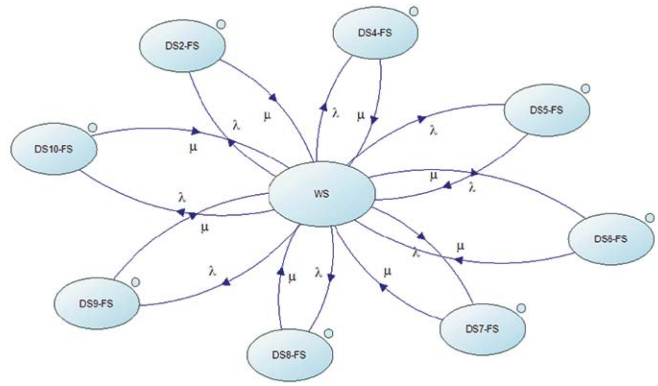

Fig.9: State diagram of D4

$$\frac{dP_0}{dt} = -\lambda_2 P_0 - \lambda_3 P_0 - \lambda_5 P_0 - \lambda_6 P_0 - \lambda_7 P_0 - \lambda_9 P_0 - \lambda_{10} P_0 + \mu_2 P_2 + \mu_3 P_3 + \mu_5 P_5 + \mu_6 P_6 + \mu_7 P_7 + \mu_9 P_9 + \mu_{10} P_{10} \quad \text{... (4)}$$

$$\frac{dP_0}{dt} = -P_0(\lambda_2 + \lambda_3 + \lambda_5 + \lambda_6 + \lambda_7 + \lambda_9 + \lambda_{10}) + \mu_2 P_2 + \mu_3 P_3 + \mu_5 P_5 + \mu_6 P_6 + \mu_7 P_7 + \mu_9 P_9 + \mu_{10} P_{10} \quad \text{... (5)}$$

$$\frac{dP_0}{dt} = -P_0 \sum_{i=1}^{7} \lambda_i + \mu_2 P_2 + \mu_3 P_3 + \mu_5 P_5 + \mu_6 P_6 + \mu_7 P_7 + \mu_9 P_9 + \mu_{10} P_{10} \quad \text{... (6)}$$

$$[\frac{d}{dt} + \sum_{i=1}^{7} \lambda_i] P_0 = \mu_2 P_2 + \mu_3 P_3 + \mu_5 P_5 + \mu_6 P_6 + \mu_7 P_7 + \mu_9 P_9 + \mu_{10} P_{10} \quad \text{... (7)}$$

$$[\frac{d}{dt} + \alpha_m] P_i(t) = \beta_m P_j(t), \quad m = 1,2,2,3......, j = 0,1.2,3....., i = 1 \text{ to } 7 \quad \text{... (8)}$$

With initial condition

$P_i(t) = 1$ when $i = 0$ and $P_i = 0$ when i > 0 ... (9)

In this steady-state, the derivative of the state probabilities in equation (4) to (9) are set to zero and solving the resulting equations recursively and obtained the following steady-state probabilities:

$P_2=X_2P_0$ $P_3=X_3P_0$ $P_5=X_5P_0$ $P_6=X_6P_0$

$P_7=X_7P_0$ $P_8=X_8P_0$ $P_{10}=X_{10}P_0$

Probability of full working state (WS) P_0 is determined by using normalizing condition below

$$P_o+ P_2+ P_3+ P_5+ P_6+ P_7+ P_9+ P_{10}=0 \quad ...(10)$$

Substituting the values of P_1 to P_7 in terms of P_0 into the normalizing condition in equation (10)

$$P_0(1+X_2+ X_{3+} X_{5+} X_{6+} X_7+ X_{9+} X_{10})=1 \quad ...(11)$$

$$P_0 \times d_0 = 1$$

$$P_0 = \frac{1}{d_0} = F(t) \quad ...(12)$$

where

$$X_2 = \frac{\lambda_2}{\mu_2}, X_3 = \frac{\lambda_3}{\mu_3}, X_5 = \frac{\lambda_5}{\mu_5}, X_6 = \frac{\lambda_6}{\mu_6}, X_7 = \frac{\lambda_7}{\mu_7}, X_9 = \frac{\lambda_9}{\mu_9}, X_{10} = \frac{\lambda_{10}}{\mu_{10}}$$

$$d_0 = 1 + X_2 + X_3 + X_5 + X_6 + X_7 + X_9 + X_{10}$$

Equation (12) is obtained methametical model from the shovel (S1) which is used in surface coal mine using Markov model. Similarly, D1, D2, D3 and D4 will follow the same procedure to generate the mathematical equation. The predicted reliability of S1, D1. D2. D3, D4 and D5 were calculated using obtained mathematical equation is presented in Table 5.

The percentage error (percentage error) is the difference between the R(t) by RBD and R(t) by Markov modelling was calculated and tabulated in Table 6. In some areas, percentage errors are often expressed as positive numbers. In others, it is correct to have positive or negative values. As mentioned in Table 6, the error between the RBD and Markov models is approximately 1-6%. Therefore, the modelling between RBD and Morkov is perfect.

Table 5: Prediction of unreliability using Markov model

Systems	S1	D1	D2	D3	D4
MTBF in hrs	43.83	110.12	126.83	67.36	62.52
F(t) Markov model	0.6127	0.6364	0.7161	0.6725	0.6410
R(t) Markov model	0.3873	0.3636	0.2839	0.3275	0.359

Table 6: Error calculation between RBD and Morkov modelling

Systems	F(t), RWB	F(t), MM	% Error
S1	0.35	0.387	0.0956
D1	0.345	0.3636	0.0511
D2	0.2501	0.2839	0.1190
D3	0.306	0.3275	0.0656
D4	0.367	0.359	0.0222

Fig.10 shows that the graph of the reliability curve for considered systems (i.e., shovel: S1) and dumpers (D1, D2, D3 and D4) with different MTBF values and it can identify the larger the MTBF, the better is the reliability over time. Fig.10 can be seen at the far right of the graph, where at 5400 hours, the reliability is still greater than 30%.

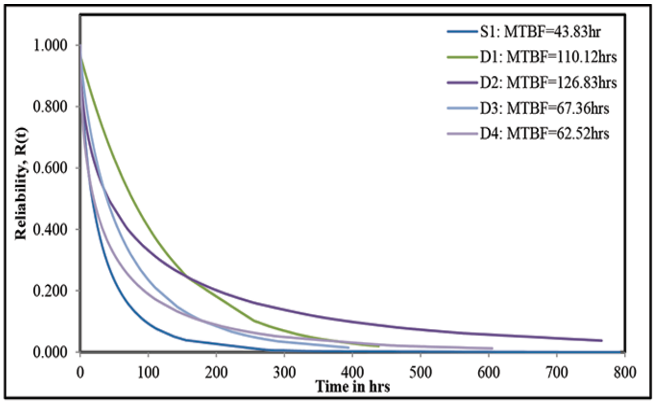

Fig.10: Effect of time in reliability

4.0 Conclusions

In this article, the purpose of the Markov technique in discovery the r(t) and f(t) of the shovel and dumper in surface mines have been discussed. The RBD diagrams and the transition diagrams show the relationship between the subsystem and its connection. The followings are key findings from the same research and analysis:

- It has been found that the total number of shovel and dumper increases overall reliability R(t) (operating reliability by 5,400 hours) in terms of time, as shown in Fig.10. There are many reasons for arm cylinder failure, engine failure in both shovel and dumper. Also due to the large volume of failures from the hydraulic system of shovel and dumper.
- A mathematical representation showed for shovel and dumper by using RBD and Markov for regular MTBF and there is no effect on MTTR.
- In this paper, an attempt has been made to assess the error between mathematical representation of the RBD and Markov is about1 to 4%.

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Conflict of interest

On behalf of all authors, the corresponding author says that there is no conflict of interest.

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