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Failure Prediction of Hydraulic Shovel Using Fault Tree Analysis

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ABSTRACT

Demands of Hydraulic shovels are continuously increasing in Indian opencast mines due to low production cost and high efficiency. Hydraulic shovels consist of large number of electrical, mechanical and hydraulic components and it is complex in design. This study involves the identification of basic root causes that are responsible for the occurrence of failure in hydraulic shovel by fault tree quantification analysis. The fault tree analysis is conducted on hydraulic shovel for predicting the shovel failure by using basic logic gate for components and its root causes. The gate-by-gate method was used to identify the probability relation for the identification of inter-relation in consecutive basic or intermediate to top event is presented. This paper, overall failure of shovel is estimated as well as the contribution of the subsystems or components in the overall prediction of failure are identified. The results showed that the categorized events (Power Generating Unit, Power Developing Unit and Power Utilizing Unit) in hydraulic shovel are having the probability of failures are 0.047, 0.0036, and 0.004 per hour respectively. These categorized intermediate events are contributed to failure of hydraulic shovel (Top event) and the probable failure of top event is 0.055742 after 2 years of operation. The study may provide a reference for future work related to the hydraulic shovel analysis, design and maintenance.

KEYWORDS: *Hydraulic Shovel, Fault Tree Analysis, Time to Failure, Reliability, Opencast mining*

1. INTRODUCTION

The demand of coal continuously increases throughout the world so the demand of HEMM required more to fulfill the target production [1–3]. In India there is 93% of coal producing by the opencast coal mining using different combination of HEMM to remove the overburden like dumper-shovel combination about 60% and dragline about 40% [4,5]. When the any failure occurrence in HEMM directly affects the productivity and reduces the reliability and safety [6,7]. The hydraulic shovel is a capital-intensive HEMM used in opencast coal mines to load the dumper [3]. Although today's shovels are very technologically advanced equipment and use the best engineering innovations, the harsh working environment of mining operations leads to breakdowns that increase the downtime losses and maintenance cost. Fault Tree Analysis (FTA) is used to predict bucket failure and understand how a bucket might fail, identify the best ways to reduce risk, and determine the frequency of occurrence of a safety incident or failure of a specific functional level [8,9]. FTA maps the relationship between faults, subsystems, and redundant elements of the safety design by creating a logic diagram of the entire system. Problems are associated with the hydraulic shovel in surface mines, which is highly time-consuming due to various breakdowns, maintenance time, repairs, etc. At the time of machine repairs and other shutdowns, they lead to production stoppages. Drawing fault tree for determining the events associated with a hydraulic bucket failure. By performing time study on a hydraulic bucket, it was found in many cases which parts of the bucket are responsible for failure and where it consumes time.

1.1. Introduction of hydraulic shovel

The Hydraulic shovels are the most extensive mobile equipment move easy for surface mining operations to remove overburden and mineral ore. It comprises a vast bucket capacity and easy handling of material. Hydraulic power is used for digging, scooping, lifting, swinging and unloading operations [10]. The hydraulic shovel's bucket is filled by bucket hydraulic cylinder in front and backward motion and the combination of all operations in hydraulic shovel leads to load the bucket fulfill efficiently. The lifting and swinging operations are effectively done by hydraulic power releasing and pressurizing into cylinders to cause the load into tippers [11].

he hydraulic shovel sits on the top of the overburden or material ore benches; usually 2 m bed mostly preferred to load the ore in tippers on the high wall side and excavates the material in front of itself to dump it on the strip's low wall or soil side to uncover the material ore or overburden. A hydraulic shovel can easily dump the excavated overburden materials to a distance of around 10m from the machine.

In this study, a hydraulic shovel (top event) with a bucket capacity of $1.8m^3$, manufactured by L&T komatsu engineering limited, PC 350 model, commissioned in the year 2005, in a large surface granite mine. The Hydraulic shovel is considered to be a system that consists of three major sub-systems: Power Generating (PGU), Power Distributing Unit (PDU) and Power Utilizing Unit (PUU). The notation used in various components of shovel as followed

HS - Hydraulic Shovel (PC 350)
PGU - Power Generation Unit
PDU – Power Developing Unit
PUU – Power Utilizing Unit
HP – Hydraulic Power
H&C – Hydraulic Cylinders
B/H C – Boom Hydraulic Cylinder
PM – Propel Mechanism
A1 – Diesel engine
A2 – Gear reduction
A3 – Hydraulic valve bank
A4 – Particulate contamination
A5 – High fluid temperature
A6 – Clogged filters
A7 – Stick hydraulic cylinder
A8 – Bucket hydraulic cylinder
A9 – Swing motor
A10 – Swing circle
A11 – Under carriage unit
A12 – Bush failure
A13 – Piston cylinder seal
A14 – Propel motor
A15– Propel gears

2. Literature Review

FTA is used to predict bucket failure and understand how a bucket might fail and identify the best ways to reduce risk, and determine the frequency of occurrence of a safety accident or failure of a specific functional level. FTA maps the relationship between faults, subsystems and redundant elements of the safety design by creating a logic diagram of the entire system [11]. FTA was developed in 1962 at Bell Laboratories by H.A. Watson, under a US Air Force Ballistic Systems Division contract to evaluate the Minuteman I intercontinental ballistic missile (ICBM) launch control system [11]. The use of fault trees has since gained widespread support and is often used by reliability experts as a failure analysis tool to understand how systems can fail, to identify the best ways to reduce risk and to determine (or get a feel for) the frequency of occurrence of a security incident or (functional) failure of a certain system level. It previously understood the logic leading to the highest event/adverse state and shows compliance with the safety/reliability (input) requirements of the system. Prioritizes contributors leading up to the top event and creates lists of critical equipment/parts for various important measures. FTA can be used as a design tool to help create requirements (output/lower level). Acts as a diagnostic tool to identify and correct the causes of a peak event and can assist with the creation of diagnostic manuals/processes.

3. Methodology

The flow chart of proposed research work shown in Figure 1. In this study two years maintenance logbook data of shovel from 2020-2022 is collected from opencast coal mine. The time study is conducted and identified the root causes in performance to the shovel. The operational data were collected from the daily report and maintenance logbook of the case study hydraulic shovel system operated in a large surface mine.

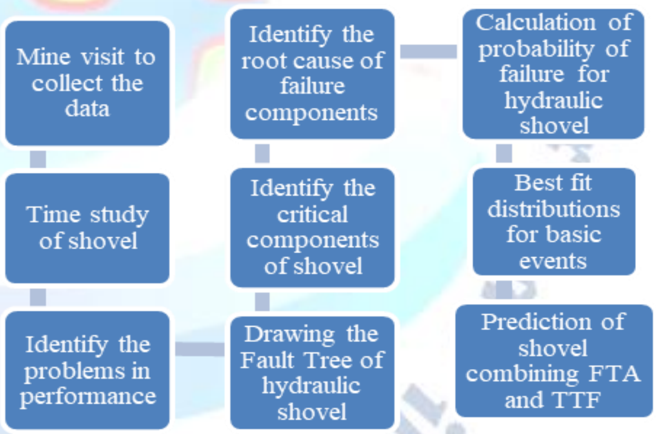

Figure 1 Flow chart proposed research work

Collected data are in raw format secondary type data and were recorded by the floor personnel for internal use. Raw data have been prepared for statistical analysis by converting to excel format, sorting and arranging in chronological order. Data have been classified to calculate time to failure (TTF) data of each subsystem and component of the dragline. Statistical analysis of ordered TTF data results estimated parameter of the best fit distribution for each intermediate event categories several components. Drawing the fault tree of hydraulic shovel using the data collected from mine and identified the critical components of shovel. The root causes of failure components are identified and probability of failure for hydraulic shovel is calculated. The data collected from the mine is calculated by formulating in the probability calculations of the basic root causes probability of failure of shovel. The reliability also determined by using easy fit software to validation the developed FTA model and estimates the error. The most popular distribution like normal, exponential and Weibull distributions used to identify the goodness of fit for survival function. The best fit distributions are drawn for basic events and developed FTA model to predict the failure of shovel.

3.1. Fault Tree Analysis of Hydraulic Shovel

The aim of fault tree quantification is to find out the probability of top event to occur when the probability of basic events occurrences are known. Basic events are may be dependent or independent. The assumption of independency makes the mathematics simpler. Dependent basic events are the result of common cause failures. There are two mostly common methods used for quantification namely; gate-by-gate method and cut set method. In this study gate by gate method are used due to simplicity of analysis by breaking down the complex system into simple components, one gate at a time. It helps in identifying the weak components of the system and their relationship with other components. It helps in identifying the dependencies between the components of the system and in understanding the how the failure of the component can affect the other components of the system. Moreover, accurate results can achieved by gate by gate method is considered to be more accurate than the cut set method and it provides a more comprehensive analysis of the systems failure modes and their probabilities. The detailed analysis is performed and it helps in understanding the complex interactions between the components of the system and their impact on the systems overall performance.

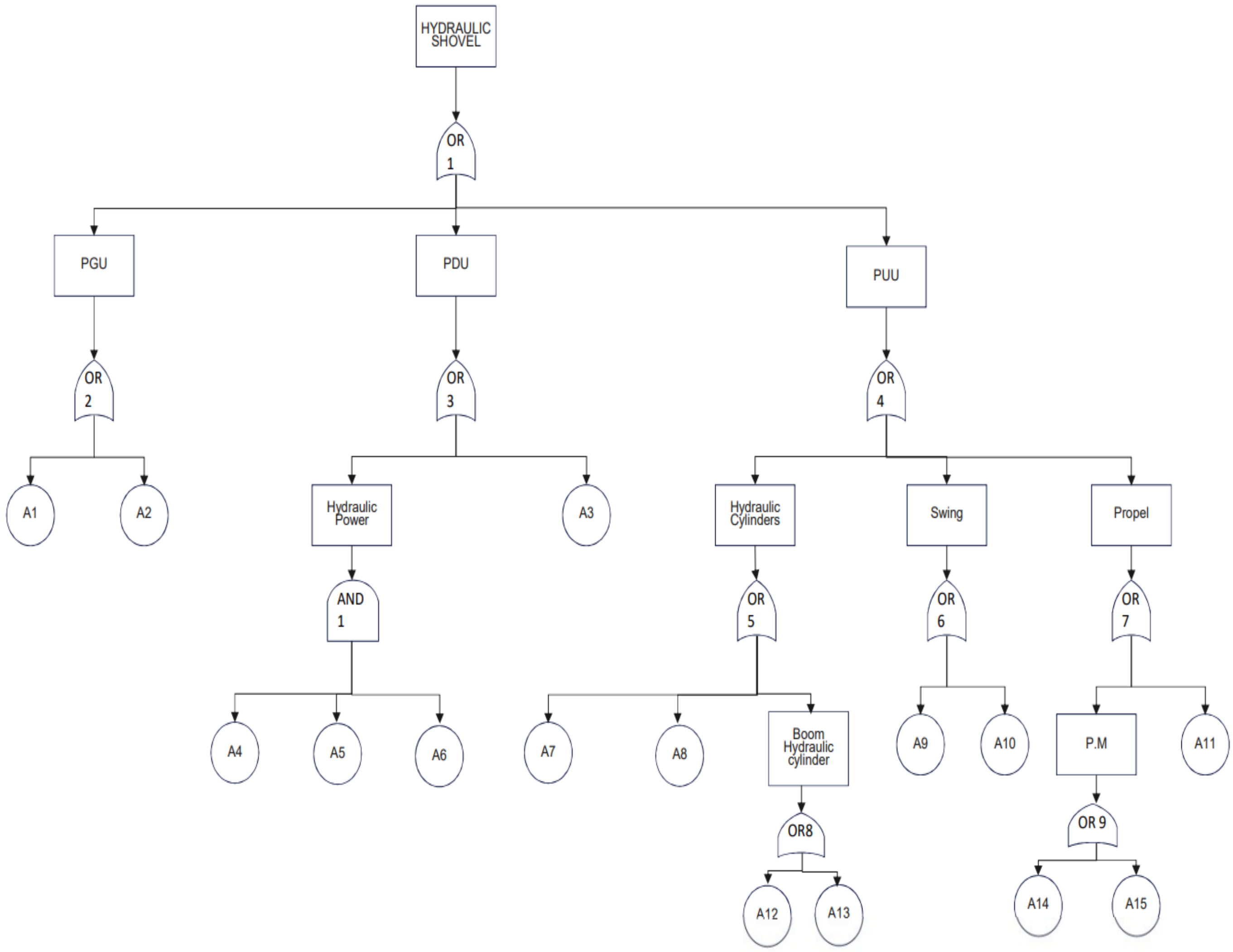

Figure 2 Fault tree quantification of hydraulic shovel

3.2. Gate-by-gate method

By the Gate-by-gate method, the probability of top event occurrence is can be found out. The engaged hours of Hydraulic shovel for working in the span of 2 years (17520

hours) is approximately 13625 hours. According to this data the probability of basic event occurrence is calculated.
Maintenance hours = 2445 hours
Stoppage hours = 730 hours
Public Holidays = 720 hours
Working Hours = 13625 hours
Formula for calculating the probability of failure basic events,

$$Probability\ of\ failure\ (Basic\ event) = No.of\ \frac{failures}{Working}\ hours \quad (1)$$

OR Gate formula,
For 2 events contribution,

P(E) = P(B1∩B2)
*P (E) = P (B1) +P (B2)–P (B1)*P (B2)* (2)

For 3 events contribution,
*P (E) = P (B1 ∩ B2 ∩ B3) P (E) = P (B1) + P (B2) + P (B3) – P (B1) * P (B2) – P (B1) * P (B3) – P (B2) * P (B3) + P (B1) * P (B2) * P (B3)* (3)
AND Gate formula,
For 3 events contribution,
P (E) = P (B1 U B2U B3)
*P (E) = P (B1) * P (B2) * P (B3)*(4)

Table 1 Calculation table of top event probability

Sl.no	Basic events	No. of Failures (2years)	Working hours	Probability of failure (Basic event)	Basic events		intermediate events	OR & AND gate Probability	Sub-System Probability		Top Event Probability	
1	A15	68	13625	0.0049908	A11		PM	Propel				
2	A14	56	13625	0.0041101	0.005504587		0.0090804	0.014535008				
3	A13	89	13625	0.0065321	A7	A8	B/H Cldr	Hydraulic cylinders				
4	A12	102	13625	0.0074862	0.005	0.006	0.0139694	0.024658621				
5	A11	75	13625	0.0055046	-	-	-	-	PUU	0.0475		
6	A10	45	13625	0.0033028	-	-	-	Swing				
7	A9	64	13625	0.0046972	-	-	-	0.007984486				
8	A8	79	13625	0.0057982	-	-	-	-			HS	0.0557
9	A7	65	13625	0.0047706	-	-	-	-				
10	A6	84	13625	0.0061651	A3		-	Hydraulic power				
11	A5	43	13625	0.003156	0.00359633		-	1.05674E-07	PDU	0.0036		
12	A4	74	13625	0.0054312	-	-	-	-				
13	A3	49	13625	0.0035963	-	-	-	-				
14	A2	31	13625	0.0022752	-	-	-	-	PGU	0.0043		
15	A1	28	13625	0.002055	-	-	-	-				

4. Result and Discussion

Data of Hydraulic shovel failure events were collected from Gowra minerals limited. Analysis of the failure data for either a time constant or the time-dependent model involves a trend analysis, selection of a best-fit distribution, and estimation of model distribution parameters. Known statistical methods were used to calculate the failure probability of each component of a dragline. Trend analysis and correlation studies were conducted using TTF data of the components of the subsystems. A goodness of fit test was carried out to obtain a statistical distribution that best fits the failure data. It was found that the Weibull distribution and normal distribution is the best fit for the failure data of the components of the case-study hydraulic shovel system. The achieved probability of failure is 0.055742 per hour and the intermediate subsystem of failure probability for PGU is 0.0043 per hour, PDU is 0.0036 per hour and PUU is 0.0475 per hour.

4.1. Reliability analysis

The failure probability of the hydraulic shovel components are identified through FTA. The TTF data of each critical component are have best fit distributions and based on best fit distributions the graph is drawn for PGU, PDU, and PUU. The estimated reliability of hydraulic shovel system is 94.42%.

Reliability formula,

$$Reliability, R\ (t) = 1 - probability\ of\ failure \quad (5)$$

Figure 3 Best fit distributions for PGU subsystem

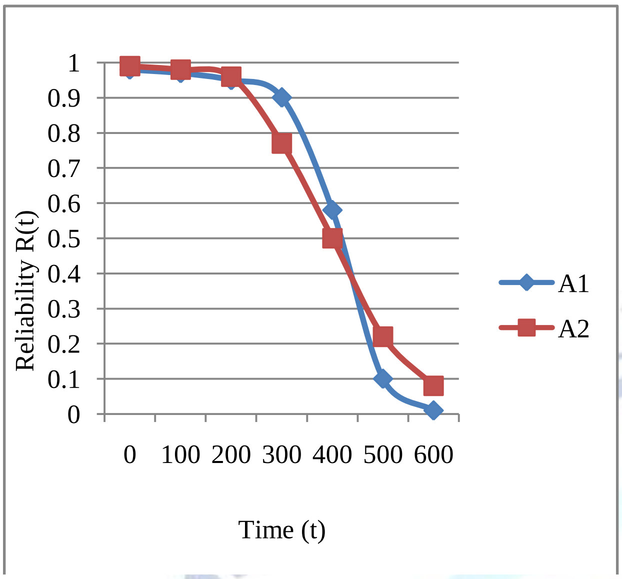

Table 2 Result of statistical analysis of TTF data of various components of Hydraulic shovel

Sub-systems	Components	K-S test(goodness of fit)			Best fit distribution	Parameters
		Exponential	Normal	Weibull		
PGU	A1	0.53756	0.12862	0.10396	Weibull	α=18.33,β=497.17
	A2	0.52019	0.12581	0.20683	Normal	σ=60.523,μ=437.66
PDU	A3	0.49541	0.07522	0.05548	Weibull	α=9.2605,β=290.73
	A4	0.48848	0.10196	0.11546	Normal	σ=26.569,μ=183.11
	A5	0.49612	0.09242	0.10506	Weibull	α=8.5087,β=330.87
	A6	0.45327	0.11007	0.09337	Weibull	α=6.1279,β=172.87
PUU	A7	0.50848	0.1287	0.15239	Normal	σ=23.417,μ=209.12
	A8	0.49151	0.10393	0.11804	Normal	σ=26.721,μ=183.31
	A9	0.4897	0.17486	0.19318	Normal	σ=31.718,μ=212.45
	A10	0.49143	0.09109	0.11237	Normal	σ=36.43,μ=301.47
	A11	0.46248	0.06396	0.07719	Normal	σ=31.713,μ=180.32
	A12	0.47654	0.12145	0.12865	Normal	σ=31.58,μ=133.07
	A13	0.44366	0.05504	0.04823	Weibull	α=6.1378,β=162.9
	A14	0.48478	0.10277	0.12662	Normal	σ=30.926,μ=242.19
	A15	0.35977	0.04614	0.04359	Weibull	α=3.817,β=218.44

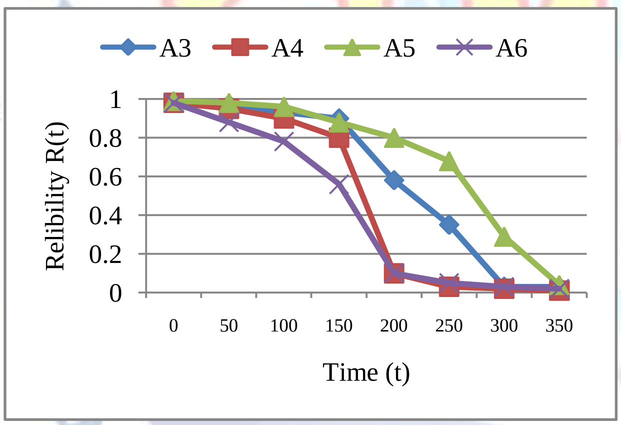

Figure 4 Best fit distributions of PDU subsystem

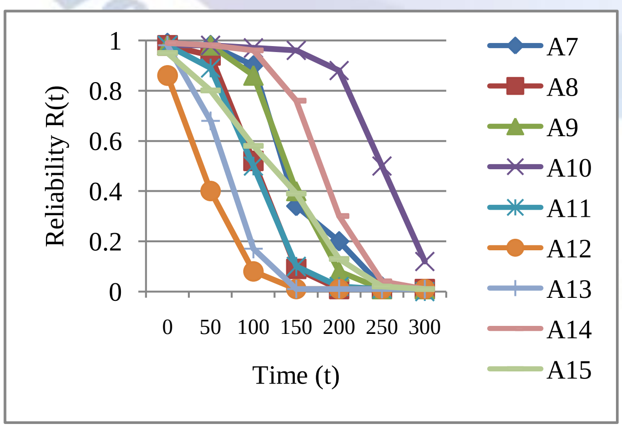

Figure 5 Best fit distributions of PUU subsystem

5. Validation

Figure 6 presents a comparative study of actual reliability of the hydraulic shovel with estimated reliability of the hydraulic shovel using FTA. It is evident from figure 6 that FTA is closer to actual reliability. For example, after 30hours of operation the actual reliability of hydraulic shovel is 85.69% and FTA reliability of hydraulic shovel is 70.65% respectively. This work defines error in prediction as follows: Error is the difference between actual and estimated values and expressed as:

$$\%error = (Actual\ reliability - Estimated\ reliability)/ Actual\ reliability * 100 \quad (6)$$

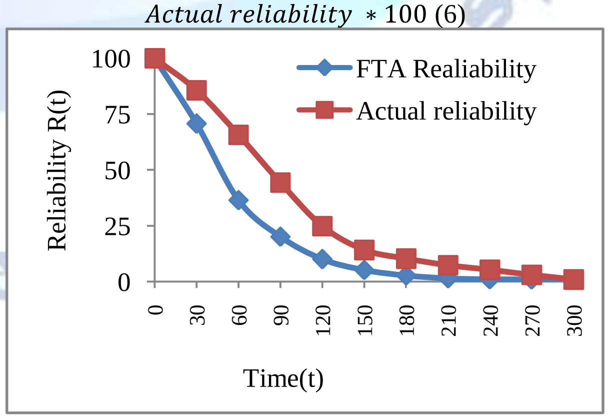

Figure 6 Comparison of FTA reliability and Actual reliability

Table 3 % Error in reliability of Hydraulic shovel with different models

	FTA	Actual reliability	FTA
t	R(t)	R(t)	R(t) % Error
0	100	100	0.00
30	70.65	85.69	0.18
60	36.51	65.76	0.44
90	20.17	44.32	0.54
120	10.05	24.89	0.60
150	5.23	14.21	0.63
180	2.81	10.32	0.73
210	1.52	7.41	0.79
240	1.12	5.3	0.79
270	1.01	3.1	0.67
300	0.85	1.1	0.23

6. Conclusion

This study presented a FTA reliability analysis of a hydraulic shovel. Failure probability, reliability and level of confidence of working with hydraulic shovel through FTA and TTF best fit distributions data have been illustrated. The Power Utilizing Unit (PUU) was identified as the most failure prone subsystem; with a 0.047 failure probability per hour followed the Power Developing Unit (PDU) with a 0.0036 and Power Generating Unit (PGU) with a 0.004 failure probability per hour.

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