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Risk Based Maintenance Planning for Loading Equipment in Underground Hard Rock Mine: Case Study

Sidharth Talan, Devendra Kumar Yadav, Yuvraj Singh Rajput, Subhajit Bhattacharjee

Abstract**—**Mining industry is known for its appetite to spend sizeable capital on mine equipment. However, in the current scenario, the mining industry is challenged by daunting factors of non-uniform geological conditions, uneven ore grade, uncontrollable and volatile mineral commodity prices and the ever increasing quest to optimize the capital and operational costs. Thus, the role of equipment reliability and maintenance planning inherits a significant role in augmenting the equipment availability for the operation and in turn boosting the mine productivity. This paper presents the Risk Based Maintenance (RBM) planning conducted on mine loading equipment namely Load Haul Dumpers (LHDs) at Vedanta Resources Ltd subsidiary Hindustan Zinc Limited operated Sindesar Khurd Mines, an underground zinc and lead mine situated in Dariba, Rajasthan, India. The mining equipment at the location is maintained by the Original Equipment Manufacturers (OEMs) namely Sandvik and Atlas Copco, who carry out the maintenance and inspection operations for the equipment. Based on the downtime data extracted for the equipment fleet over the period of 6 months spanning from 1st January 2017 until 30th June 2017, it was revealed that significant contribution of three downtime issues related to namely Engine, Hydraulics, and Transmission to be common among all the loading equipment fleet and substantiated by Pareto Analysis. Further scrutiny through Bubble Matrix Analysis of the given factors revealed the major influence of selective factors namely Overheating, No Load Taken (NTL) issues, Gear Changing issues and Hose Puncture and leakage issues. Utilizing the equipment wise analysis of all the downtime factors obtained, spares consumed, and the alarm logs extracted from the machines, technical design changes in the equipment and pre shift critical alarms checklist were proposed for the equipment maintenance. The given analysis is beneficial to allow OEMs or mine management to focus on the critical issues hampering the reliability of mine equipment and design necessary maintenance strategies to mitigate them.

Keywords**—**Bubble matrix analysis, LHDs, OEMs, pareto chart analysis, spares consumption matrix, critical alarms checklist.

Sidharth Talan is Graduate Engineer Trainee at Vedanta Resources Ltd, Udaipur, Rajasthan, India 313004 (phone: +91-9800126123; e-mail: Sidharth.Talan@ vedanta.co.in).
Devendra Kumar Yadav is Engineering Head at Sindesar Khurd Mines, Dariba, Rajasthan, India 313211 (phone: +91-8003699466; e-mail: Devendra.Yadav@vedanta.co.in).
Yuvraj Singh Rajput is Associate Manager at Sindesar Khurd Mines, Dariba, Rajasthan, India 313211 (phone: +91- 9829205277; e-mail: Yuvraj.Rajput@vedanta.co.in).
Subhajit Bhattacharjee is Associate Manager at Sindesar Khurd Mines, Dariba, Rajasthan, India 313211 (phone: +91- 9929844560; e-mail: Subhajit.Bhattacharjee@vedanta.co.in).

I. Introduction

OVER the past few years, the mining equipment has become increasingly complex and sophisticated to tackle the escalating tonnage plans of the mining companies. This in turn makes it extremely cost ineffective to have standby units at the mine site. Although the lower demand and fall in prices of the commodities have forced the miners globally to undergo reduction in their capital expenditures, investment in property, plant and equipment (PPE) still accounts for more than 50% of their total assets [1]. To enhance the mine productivity, mining companies have significantly inclined their focus toward the equipment reliability and their maintenance planning operations [2]. Today, for highly performance demanding scenario in this industry, it is a daunting task for the engineers to maintain acceptable equipment availability by engineering the reduction in downtime incidents in the equipment, conserving the equipment deterioration and ensuring the safe and environmental friendly equipment performance [3]. Maintenance operations at the mine sites often suffer from irregularities in planning and the defensive mind set of management which gets too occupied by crisis maintenance to focus solely on preventive maintenance of the equipment [4]. The maintenance planning has to shift towards more optimized and predictive approach [5], taking into consideration the reliability and the impact of failure of each key component of the machine operating in the mine. Nevertheless, mining companies globally are gradually shifting towards Reliability and Condition focused maintenance planning while slowly incorporating the risk of downtime of the equipment in their calculations. RBM Planning approach which was introduced first in chemical engineering and petroleum fields has gain acceptance in wide range of industrial fields such as steel making and shipbuilding etc. [6]. RBM is designed to study the risk associated with the downtime components and factors in the machine and prioritize the maintenance operation with respect to risk associated with each of them [7]. This paper aims to design the maintenance plan for the haulage equipment operating in the case study mine based on risk focused approach.

RBM in broad consists of two phases, i.e. risk evaluation of the downtime components and factors in the equipment and inspection and maintenance planning of the critical factors in the machine. The risk evaluation is further segregated into two steps [8], namely evaluation of probability of occurrence of failure in the inspecting areas of the machines and the impact of occurrence of the failures which could be evaluated using the loss of production in ore from the mine due to equipment downtime. The risk factor used for prioritizing the failures is generally taken as the product of the probability of occurrence of the failure and the impact associated with it. The inspection and maintenance planning approach for the critical risk components and factors aims to focus on corrective practice procedures while inspecting the critical components during planned maintenance operations and stock planning of the spares and components of the machines more prone to failures derived from their risk factors. Fig. 1 showcases the general RBM approach implemented across industries. The downtime data collection for the operational equipment at the mine site plays a significant role in contemplating maintenance planning.

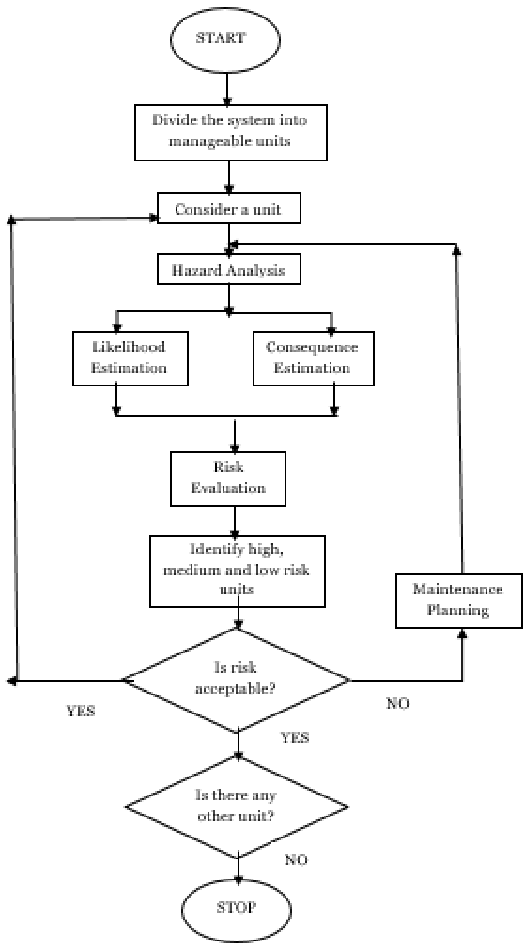

Fig. 1 General RBM approach [5]

II. Materials and Methods Used

A. Case Study

The study has been carried out at Hindustan Zinc (a flagship company of Vedanata Resources plc) operated Sindesar Khurd Mines (SKM) in Dariba, Rajasthan. SKM is an underground zinc and lead mine, while also producing silver as the byproduct. The mine has an annual ore production of roughly 4 Mt per annum. The mining method implemented for extraction in the mine is cut and fill mining. Simultaneous operations in the form of development of drives and galleries and the ore production from the mining stope take place in the mine. The material extracted after drilling and blasting is hauled from the drawpoints to the loading points by the LHDs. The ore from the loading points is filled into LPDTs, which further haul the ore to the surface based stock piles.

The equipment studied in the paper consists of both Sandvik and Atlas Copco manufactured loading machines. Sandvik made machines consisted of 17 tonnes capacity LHDs. On the other hand, Atlas Copco made machines consisted of 10 tonnes capacity LHDs. All the equipment is maintained and inspected by the respective manufacturers in their workshops at mine site.

The scheduled maintenance operations carried out by equipment manufacturers are pursued on the basis of regular time based engine running hours of each machine. After every 125, 250, 500, and 1000 engine running hours of the machine, there is a scheduled maintenance of 6, 8, 10, and 24 hours for the respective machine. Apart from that, before every shift, 30 minutes of pre-shift checkup is carried for each machine.

B. Data Collection

The data collected from the mine consisted of shift wise downtime data for each of the haulage equipment operating in the mine over the course of 6 months, i.e. January 1, 2017 until June 30, 2017. The data depicted the time span and the occurrence date of each downtime event for each of the loading equipment in the mine. The Daily shift reports maintained by equipment manufacturers for their daily shift wise equipment maintenance and inspection carried out in their respective workshops were studied for the given 6 months period. The alarm logs data depicting the alarm signals and warnings for different critical components in the machine were also analyzed for the given equipment.

Apart from that, the equipment wise productivity, availability and utilization data were studied for last 6 months in addition to the daily price statistics of the zinc, lead and silver prices for the given time scale. Lastly the consumption statistics of the spares are used by the equipment manufacturers during the events of downtime and scheduled maintenance operations of the machines.

C. RBM Analysis

For RBM Analysis, the downtime events in the equipment were segregated into primary categories based on the components assemblies within the equipment. The primary downtime categories were prepared separately for each fleet of the equipment as mentioned in the previous section. The primary downtime categories for Sandvik 17 tonnes fleet as an example were AC (Air Conditioner), AFSS (Automatic Fire Suppresion System), Braking system, Cabin system, Drive, Electrical, Engine, Hose punctures/leakages, Hydraulic system, Parking and Starting, Pillow, Radiator, Transmission system, Turbocharger, Tires, Water pumps and Wheel stud. Reliability and maintenance indicators such as Mean Time

Between Failures (MTBF) and Mean Time To Repair (MTTR) were evaluated for all the primary downtime categories. MTTR is the average time consumed for the repair process for each downtime type for each equipment during the time period analyzed (6 months for the given analysis) whereas MTBF is the average time period between two consecutive downtime events of similar type for each equipment during the time period analyzed.

The Risk Factor was computed for each primary downtime categories for each downtime fleet through the product of rate of failure (1/MTBF) and the impact of occurrence taken as the production loss in the mine due to unavailability of each of the equipment. The Risk Factor computation is depicted using (1).

$$Risk\ Factor\ (R) = (1/MTBF) \times (MTTR \times Average\ Planned\ Productivity \times Average\ Availability \times Average\ Utilisation) \quad (1)$$

Here Average Productivity refers to the arithmetic average of the monthly productivity planned for each month. Average Availability refers to the arithmetic average of the monthly availability achieved by each equipment fleet during the time period considered for analysis whereas the Average Utilisation is the arithmetic average of the monthly utilisation percentage of the planned available time, achieved by each equipment fleet during the time considered for analysis.

The Risk Factors were utilized for prioritizing the critical downtime categories to focus upon for further analysis. Thus, Pareto Chart Analysis was conducted based on the Risk Factors computed and the critical downtime categories contributing 80% of the cumulative risk factors were shortlisted for further analysis.

The critical downtime categories were further studied for sub or detailed downtime classifications under each of the categories or combinations of each of them. For the given stage, Bubble Matrix Analysis was conducted consisting of a matrix, which was constructed utilizing the two indicators namely Total Downtime Span and Downtime Frequency for each of the sub-downtime categories for each equipment fleet derived from previous stage. The bubbles were marked with Total Downtime Span on the vertical axis and the Downtime Frequency on the horizontal axis. The critical sub categories of downtimes were further shortlisted from the Bubble Matrix Analysis for each fleet of equipment.

The next process in the analysis was to identify the criticality of each of the shortlisted sub categories of downtimes from the previous process in each of the equipment of all the haulage fleets. The criticality of downtime was evaluated by using the product of frequency and span (total breakdown hours) of downtime over the time period of analysis. Equation (2) showcases the evaluation of Criticality of downtime sub categories. Top 3 or 4 equipment based on their Criticality score were shortlisted for further scrutiny.

$$Criticality = Total\ breakdown\ time\ (hours) \times Frequency\ of\ downtime \quad (2)$$

The DailyShift Reports prepared by the OEMs for the maintenance and inspection jobs conducted for each equipment in their respective workshops were alayzed to accumulate detailed information regarding the downtime causes, remedy procedures adopted by OEMs and the spares damaged during the downtime events. Monthly spares consumption report provided detailed insight into the specific type of spare (identified through its model number) and the quantity of the same consumed in a month in each of the equipment.

The daily alarm logs generated by each equipment of the fleet were analyzed based on the results obtained from the preceding steps to contemplate the critical alarm check points for the entire fleet to be incorporated in the preshift monitoring, in order to become a source of predictive failure analysis for the equipment.

III. Results

Table I expresses the Risk Factors evaluated for the primary downtime categories for Sandvik 17 tonnes equipment fleet. The Primary Categories constituting top 80% of cumulative Risk Factors were evaluated to be Hydraulic, Transmission, Engine, Boom and Bucket and Axle. The Pareto Chart showcased through Fig. 2 substantiates the findings.

TABLE I
Risk Factors for the Primary Downtime Categories

Primary Downtime Categories	Risk Factor
AC	4.2
AFSS	0.5
Articulation	8.0
Axle	13.4
Boom and bucket	19.7
Brake	5.8
Cabin	2.7
Drive	7.7
Electrical	6.6
Engine	25.3
Feed and Boom	0.3
General Check	1.4
Hose	7.9
Hydraulic	52.0
Maintenance	136.3
Overheating	11.3
Parking and Starting	17.4
Pillow	0.3
Radiator	6.2
Torque Convertor Job	1.0
Transmission	26.4
Turbocharger	0.6
Tyres	1.7
Water pumps	1.2
Wheel studs	1.3

Hydraulic, Transmission and Engine Downtimes were found to be common among all the fleet of loading equipment and thus were shortlisted for further scrutiny. The above mentioned primary categories were further studied to analyze the downtime sub categories constituting each of the above. Fig. 3 shows the Bubble Matrix constructed for the 17 tonnes loader fleet. The critical sub categories evaluated from the Bubble Matrix construction were found to be Hydraulic oil leakage, leakages in other components, Overheating, Gear shifting problem and NTL (Not Taking Load) problem as highlighted in the shaded portion of the matrix. The following sub categories were further analyzed using DSR.

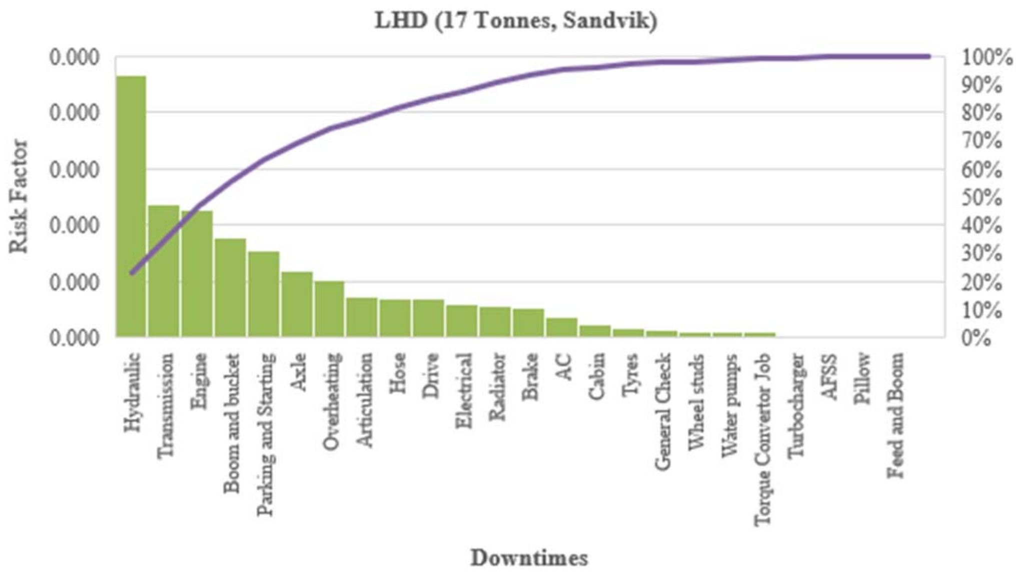

Fig. 2 Pareto Chart for the Primary Downtime Categories for 17 tonnes LHDs

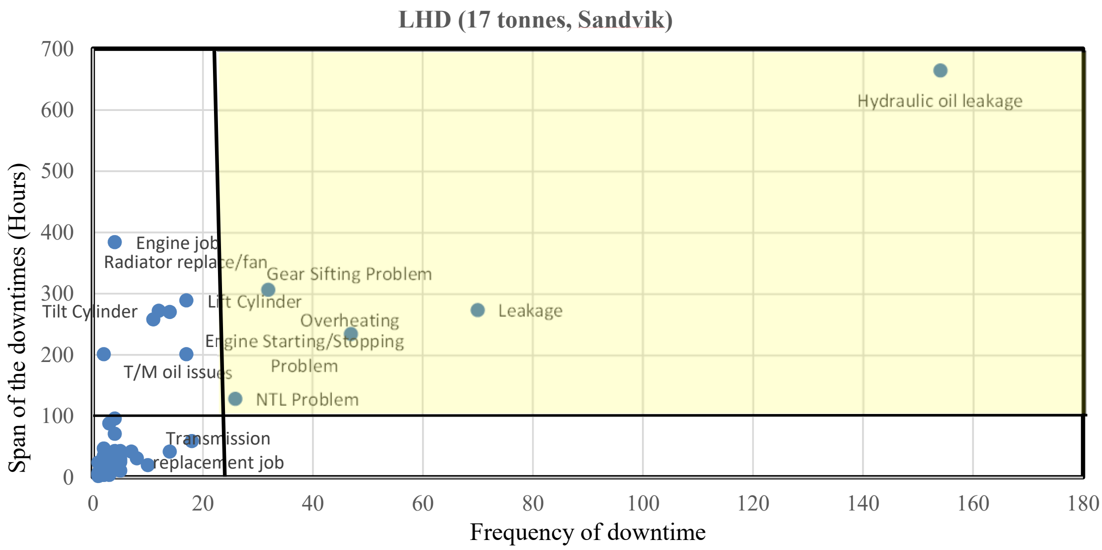

Fig. 3 Bubble Matrix for Downtime Subcategories 17 tonnes LHDs

Figs. 4-7 show the equipment wise Criticality evaluation for each of the downtime subcategories (Overheating, Gear Shifting Problem, NTL Problem and Leakages including Hydraulic Leakages respectively) evaluated from the Bubble Matrix. The showcased results are for 17 tonnes LHD fleet equipment.

Table II shows a brief outlay of the Spare Consumption Matrix developed in order to understand the equipment wise consumption of spares designated by Spare Model Number and the frequency of their usage in the downtime events over the analyzed time period.

Based on the Spares Consumption Matrix developed for the each of the spares consumed over analyzed time period, the consumption of the above-mentioned spares was found to be among the highest consumed spares for 17 tonnes LHDs over the analyzed time period. Further investigation into the downtime events corresponding to the given spares consumption instigated some design modifications in the machine assembly. Apart from that, the study of alarm logs over the analyzed time period led to proposal of critical alarm check list to be verified before each shift every day.

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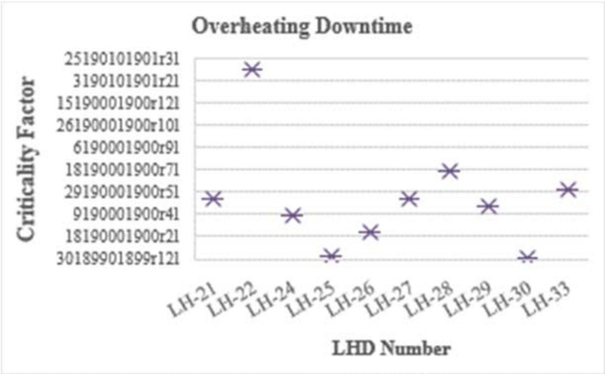

Fig. 4 Criticality Factors of 17 tonnes LHDs for Overheating problem

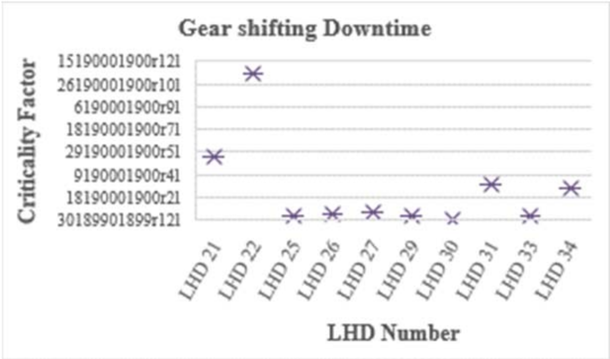

Fig. 5 Criticality Factors of 17 tonnes LHDs for Gearshifting problem

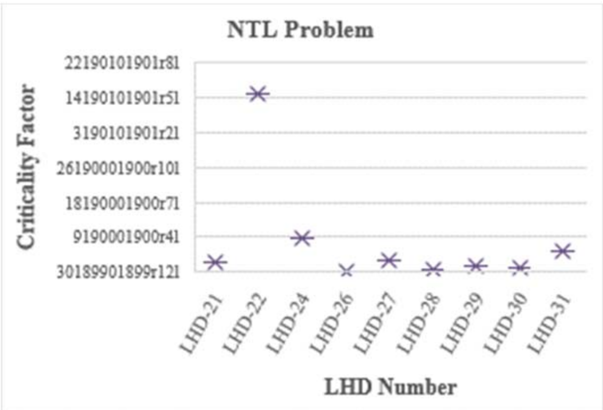

Fig. 6 Criticality Factors of 17 Tonnes LHDs for NTL problem

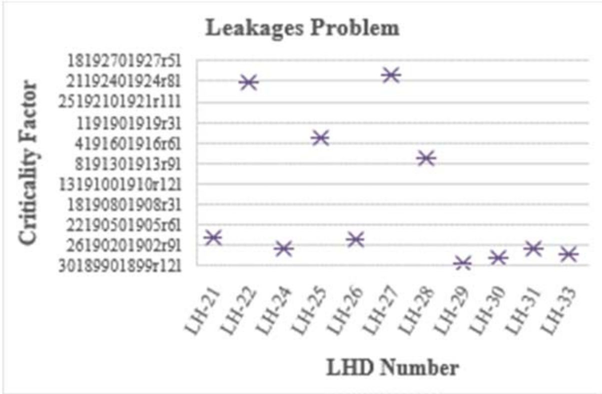

Fig. 7 Criticality Factors of 17 tonnes LHDs for Leakages problem

IV. Discussions

The spares fitment locations in LHDs were detected using the equipment's Spare's Manual received from OEM. Fig. 8 gives showcases the fitment location of Hose (Model No- 56029993) and O-Ring (Model No- 937307) in the Hydraulic Assembly of the LHDs. The study of the design with the aid of engineers at the site revealed the high bending radius of the hose mentioned as the most probable reason for its frequent breakage, supplemented by high Hydraulic Oil pressure flowing through it and the vibration during the movement of the machine. The hose failure also triggered the failure of the given O-Ring connecting the hose to the rest of the assembly. Thus, to rectify the problem, alternate hose path was proposed by the engineers, which would eliminate the given alignment and positioning of the hose and O-Ring. Fig. 9 depicts the solution design proposed by engineers.

Table III depicts the Critical Alarm Checklist for LHDs after analyzing the frequency of occurrence of the alarms over the analyzed time period.

TABLE II
Spare Consumption Matrix

Spare	Model Number	LHD21	LHD22	LHD24	LHD25	LHD 26	LHD 27	LHD 28	LHD 29	LHD 30	LHD 31	Frequency of downtimes	Quantity
O-ring	9370307	37	25	31								30	93
O-ring	9370309	2	4	2								4	8
O-ring	9370308	8	8	10								10	26
O-ring	9370301	18	28	10	14	6	8			22	6	27	112
O-ring	9370302	29	52	25	6	4						29	116
Hose	56029993	4	4		5	3	2	3	1	7	6	25	35
Hose	56023286	4	5	1	1	2	1	5	4	3	2	18	28
Hose	56027521	2	2	2	2	2	5	2		2		19	19

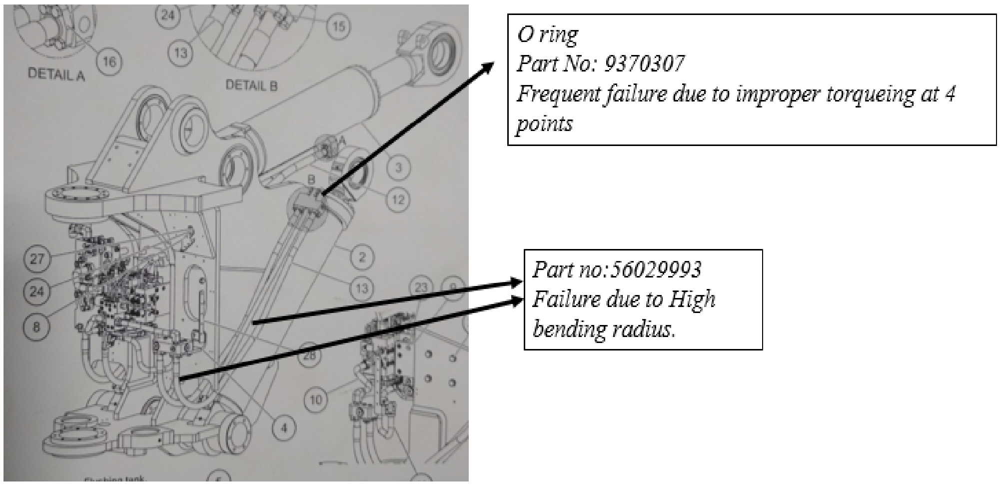

Fig. 8 Hydraulic Assembly Hose and O-ring locations and problems

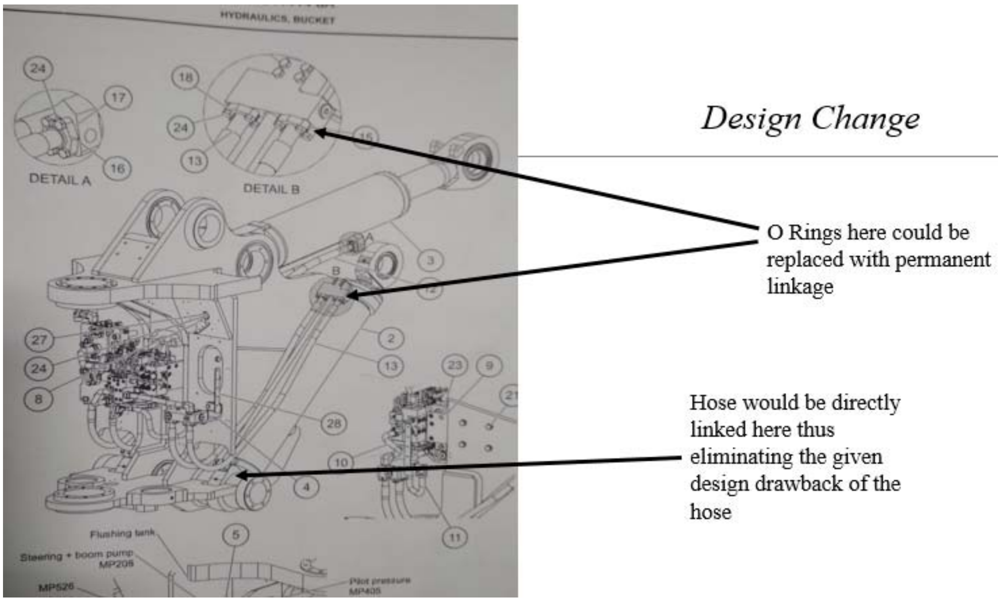

Fig. 9 Proposed Design change it the Assembly

TABLE III
CRITICAL ALARM CHECKLIST FOR LHDS

Critical Alarm Categories	LHD 21	LHD 22	LHD 23	LHD 24	LHD 25	LHD 26	LHD 27	LHD 28	LHD 29	LHD 30	LHD 31	LHD 33	LHD 34
Clutch Pressure Switch Alarm													
Central Lubrication. No pressure Alarm													
Coolant Temperature Alarm													
Turbocharger Waste gate Alarm													
Brake Circuit Charge Pressure high/low													
Fuel Pressure sensor Alarm													
Front Brake Circuit Pressure Alarm													
Oil Temperature High Alarm													
Transmission Oil Pressure High/Low Alarm													
Brake oil temperature Alarm													
Up box temperature Alarm													
Pressure difference between front/rear brake circuit ,brake may drag													

V. CONCLUSION

This study has pinpointed the key areas of focus for all the loading equipment in the mine through step wise analysis of the critical downtimes impacting the equipment. The following study has the potential to assist the mine management to focus on the specific critical areas in the machine and devise predictive maintenance procedures to reduce them or rectify the areas of concern. The RBM procedure is advantageous for the maintenance team in terms of allotting the equipment and labor towards critical downtime issues plaguing the equipment which in turn improves the productivity of the workforce and in turn availability of the equipment utilized at the mine site.

ACKNOWLEDGMENT

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