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Failure mode, effects and criticality analysis of dragline components and evaluation of risk priority number for effective maintenance planning

The occurrences of unexpected failures in heavy earthmoving machines (HEMMs) lead to the downtime that reduces the productivity, safety, and reliability of the machines. Unwanted failures increase the likelihood of unplanned maintenance activities. Dragline is an HEMM used in the opencast coal mines for removal of the overburden and its failure is undesirable as the capital invested on draglines are very high. This paper utilises the failure mode, effects and criticality analysis (FMECA) to identify the critical failure components of the dragline system and their root causes. Seven subsystems and thirty components for failure have been identified in the two-year maintenance record 2014-16 of dragline. Risk estimation has been carried out for the dragline components to estimate the risk priority number (RPN) considering four factors: failure occurrence, production loss, degradation in performance, and detectability. The RPN is used to categorise the components into three groups: high, medium, and low risk components. Based on the risk groups of component, the inspection interval and inspection time can be optimised to avoid the unexpected failure of the component and eventually improving the productivity of the dragline system.

Keywords: *Dragline; FMECA; risk priority number; maintenance; HEMM*

1. Introduction

In the present scenario of continuously increasing demand for coal, mining industry uses sophisticated HEMMs like dragline. Dragline is a capital-intensive heavy earthmoving machine (HEMM) used in opencast coal mines for removal of overburden (Li and Liu, 2013; Ponnusamy and Maity, 2016). The occurrence of unwanted failures of dragline directly affects the production, reduces the safety, reliability and increases the downtime losses (Demirel and Golbasi, 2016; Rai, Yadav, and Kumar, 2011). It is reported that unwanted failures significantly impact the machine performance, and maintenance cost of the mining machinery that shoots up to 40–50% of the total operating cost (Golbasi and Demirel, 2017). In order to decrease the failures, it is necessary to increase the failure prediction and reliability of the system. Identification of critical components and ranking of RPN can optimise the maintenance planning activities (Carmignani, 2009; Mzougui and Felsoufi, 2019; Y. Wang, Cheng, Hu, and Wu, 2012; Xiao, Huang, Li, He and Jin, 2011). The advantages of using failure mode, effects and criticality analysis (FMECA) is its suitability for criticality analysis of the system to improve the maintainability, reliability, and safety (W. L. Chang, Pang and Tay, 2017; Kim and Zuo, 2018; Passath and Mertens, 2019; Sutrisno, Gunawan and Tangkuman, 2015).

The FMECA is used for systematic evaluation of the failure occurrence, safety and detectability of potential failure modes and to fully understand the causes and their effects on the performance of the system (C. L. Chang, Liu and Wei, 2001; Sharma, Kumar and Kumar, 2005). The wide industrial application of FMECA can be observed in the areas of energy generation industries (Feili, Akar, Lotfizadeh, Bairampour and Nasiri, 2013; Rajput, Malvoni, Kumar and Tiwari, 2019; Renjith, Jose kalathil, Kumar and Madhavan, 2018), wind turbines (Arabian-Hoseynabadi, Oraee, and Tavner, 2010; Scheu, Tremps, Smolka, Kolios and Brennan, 2019; Sinha and Steel, 2015), hydraulic systems (Sharma et al., 2005), sludge treatment industries (Adar, Ince, Karatop and Bilgili, 2017), semiconductor industries (Chen, Wang, Wang and Huang, 2010), automobile and vehicle industries (Renu et al., 2016; Zhou and Thai, 2016), and in machine tools (H. W. Lo, Liou, Huang and Chuang, 2019). In mining industry, the failure mode and effects analysis (FMEA) based reliability modelling is used to identify the risk of various subsystems of the load-haul-dumper (LHD) deployed in underground mining focusing on their root causes (Balaraju, Govinda Raj and Murthy, 2019). Moreover, the FMEA is used in the yacht system design to rank the failure modes depending on the risk priorities number to take corrective actions (Helvacioglu and Ozen, 2014).

In this paper, the FMECA of the components of the dragline is proposed to estimate the RPN by multiplying four factors: occurrence, production loss, degradation in performance, and detectability. These factors are used to identify the critical components of the system. Thereafter, the

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RPN value is used to categorise the critical component into three different groups: high, medium and low risk components, which can assist the maintenance engineer to optimise the inspection interval and inspection time of the components of the dragline.

2. Description of dragline deployed in the coal mine

A walking dragline 24/96 having bucket capacity of 24 m^3, and boom length of 96 m is considered for the study. Dragline consists of a large number of electrical, mechanical, hydraulic components. All components of the system are subjected to rigid quality control. The schematic diagram of various components of dragline is shown in Fig.1. The rotate frame, which supports the walking gear, house and front-end equipment, is mounted on top of the base and is driven by three motors and gearbox assemblies. A roller ring assembly supports the rotate frame on the base. A dust-proof enclosure on top of the rotate frame, called the house, accommodates the drag and hoist machinery, swing system, and the walk motors of the system. The operator's cab is a separate unit fitted in the front right-hand side of the dragline.

The electrical power (6.6 kV, 50 Hz) is fed through the trailing cable to a collector assembly mounted on the base centre post of the rotating frame. The high voltage electrical power is fed to a high voltage cubicle in the machine house and it operates the motor-generator set (M-G set), synchronous motors, and auxiliary transformer. There are four basic motion systems of dragline: a drag system which moves the bucket backwards and forward, a hoist system which moves the bucket up and down, a swing system which rotates the rotating frame, and a walking system to move the dragline from one place to another. All motion systems are powered by D. C. motor fed from adjustable armature voltage generators. For each motor, there is an associated generator. The same generators power the drag and walk motors depending on the required motion being selected by the operator. Both the drag and hoist system consists of two force-ventilated 1300 hp, 475 V, 700 rpm D.C. motors and it is controlled through the parking brake. The swing system consists of three force-ventilated 640 hp, 475 V, 820 rpm D.C. motors, whereas walking system comprises two force-ventilated 640 hp, 475 V, 820 rpm D.C. motor. Two motor-generator (MG) set, each consists of helical gears and parking brake, are driven by 1750 hp synchronous motor.

Dragline is used for stripping overburden lying above the coal seam and to dump them into the de-coaled area in surface coal mines. The overburden stripping starts with swing of the empty bucket to the digging position with the help of hoist and drag system. Then bucket is pulled towards the machine so that bucket is dragged along the surface of the material that is controlled by drag system, while digging depth is regulated and controlled by the hoist system. When the bucket is filled, the operator takes on the hoist system to lift and move the bucket upward and loose the drag rope to move the bucket outward of the machine and swing to the dumping position which is controlled by the swing system. After that dump, the unloaded bucket moves back to digging position and the cycle is repeated.

3. Methodology

The sequence of processes for criticality analysis of dragline using FMECA to estimate the risk is shown in Fig.2 (Arunraj and Maiti, 2007; H.-W. Lo and Liou, 2018; Z. Wang, Ran, Chen, Yu and Zhang, 2020). The first step is to collect the failure data from the maintenance worksheet, inbuilt sensors, and to convert them into valuable information.

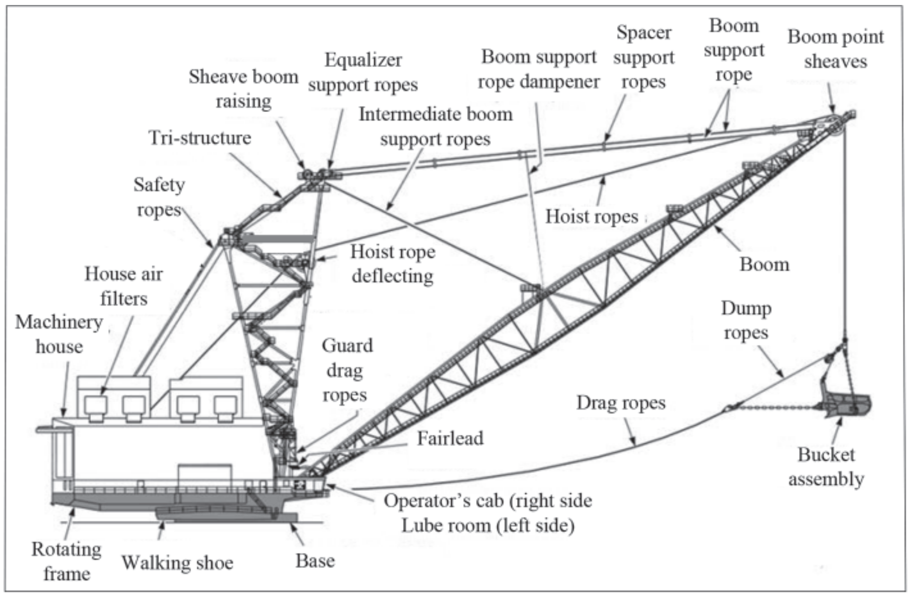

Fig.1 Schematic diagram of dragline

The starting point of an FMECA is usually to identify the failure mode and construct the block diagram for the dragline system based on historical failure data and maintenance record, and to outline the functions of system and subsystems of the dragline. The failure components belonging to each subsystem of the dragline are identified, and their failure types and possible root causes are identified using expert judgement and maintenance record as shown in Fig.3.

The risk of each component is associated with the likelihood of occurrence of failure (α), loss of production in terms of breakdown time losses (β), failure effect that degrades the performance of the system in terms of occurrence of defect in the

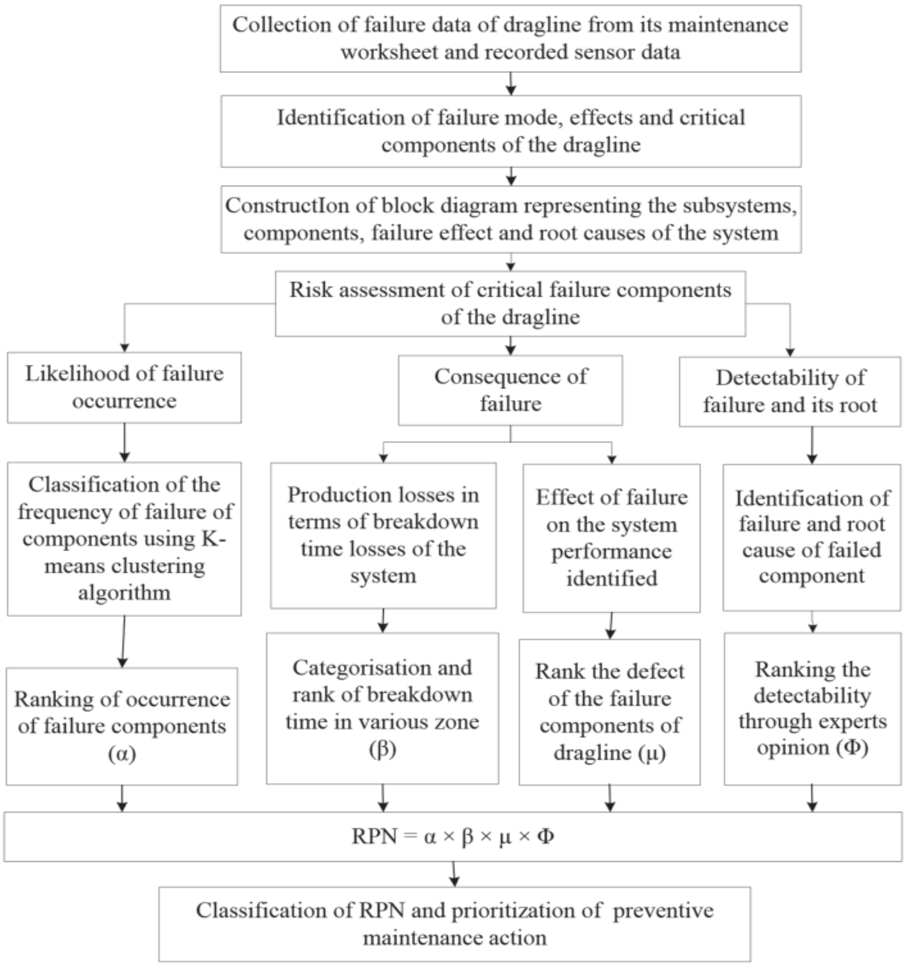

Fig.2 Flow chart of criticality analysis and assessment of RPN of dragline

component (μ), and detectability in terms of identification of failure and its root cause (Φ). To estimate the criticality of the component using RPN is given in Eq (1):

$$RPN = \alpha \times \beta \times \mu \times \Phi \qquad ... (1)$$

The estimation of α, β, μ and, Φ are described in detail in section 4 for the estimation of RPN.

4. Case study

In the case study, a walking dragline (Model: WD24/96 made by HEC Ransom and Rapier, commissioned in 9th May 2014) has been deployed in an opencast coal mine of Northern India is operating. Data collected from commissioning of the dragline to 22nd September 2016, when the engine hourly machine rate was 7267:30. In the collected data, the frequency of failure of dragline was 208 and breakdown time was 4955 hours. The frequency and breakdown hours are quantified values directly obtained from the maintenance worksheet. The dragline failure components are categorised into seven major subsystems such as bucket, rope, main unit, structure, drive system, lubrication system, and trailing cables.

4.1 Estimation of the occurrence of failure

The occurrence of failure in the dragline system is defined in terms of frequency of failure (f) of the component. In the collected data of the dragline, the frequency of failure of dragline was 208 in 30 components of the dragline. Based on the failure frequency, the occurrence of failure of components are divided into five qualitative categories such as improbable, remote, occasional, probable and frequent failures. The categorisation of failure frequency into five classes has been done using k-means clustering algorithm using SPSS v.19 statistical package (SPSS, 2010). The k-means clustering algorithm is used to group similar data points in one cluster, and k-means fix the number of clusters (k=5 for this case) and give the training results quickly (Yiakopoulos, Gryllias and Antoniadis, 2011). Initially, the random cluster centre is selected and after three iterations the error became zero as presented in Table 1.

Table 1: Ranking of the occurrence of failure (Á) using k-means clustering algorithm

Iteration	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Initial cluster centre	1	7	13	17	25
First iteration	0.93	0.125	1	1	1
Second iteration	0	0.411	0.5	0	0
Third iteration	0	0	0	0	0
Final cluster centre	1.93	6.71	11.5	16	24
Final cluster boundary	$f<4$	$4<f<9$	$9<f<14$	$14<f<19$	$f>19$
Number of components in the cluster	15	7	3	3	2
Criteria	Improbable	Remote	Occasional	Probable	Frequent
Rank	1	2	3	4	5

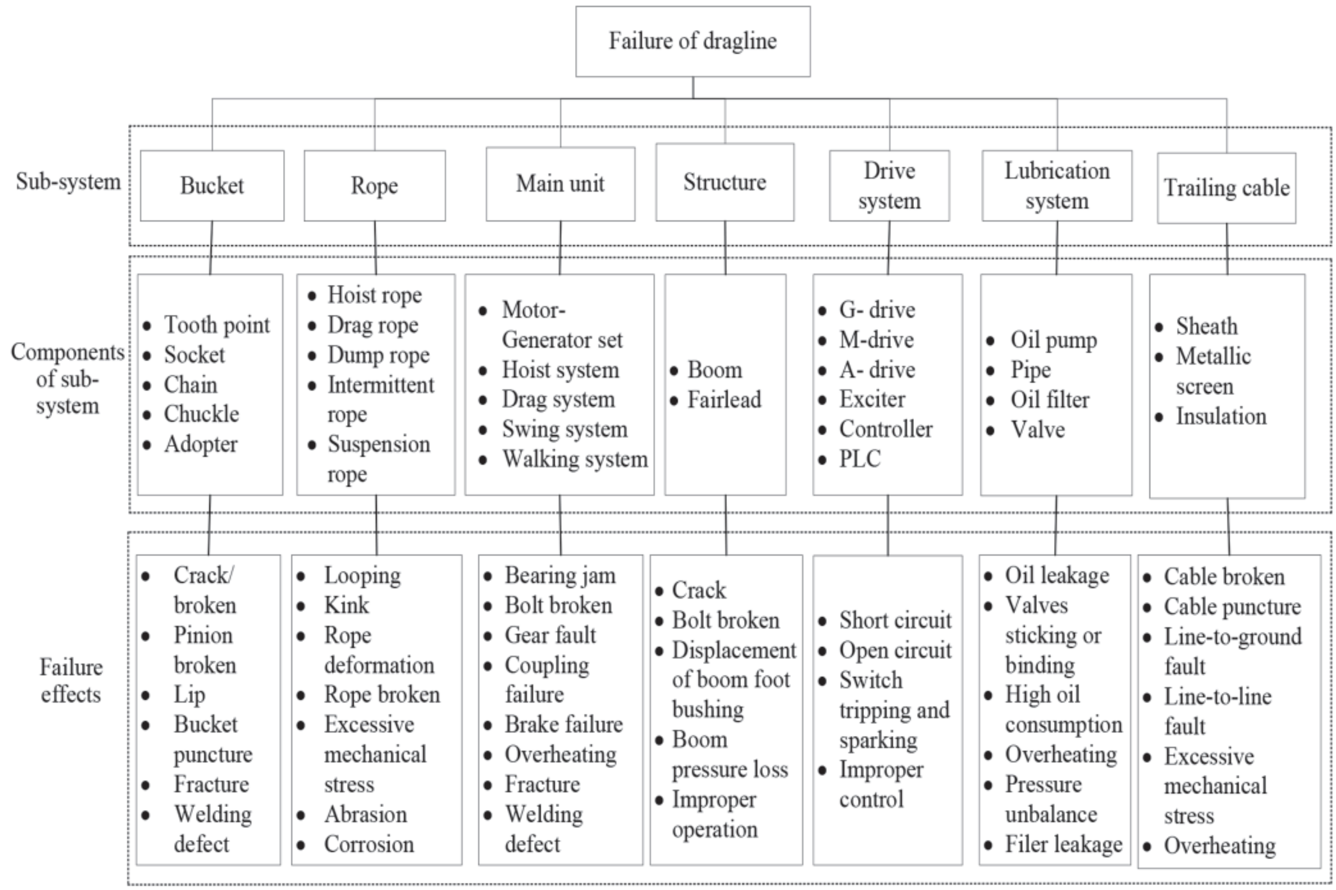

Fig.3 FMECA of various subsystems of dragline

4.2 Estimation of the consequences of failure

The objective of estimating the consequences of failure is to quantify the potential consequences of the credible failure scenario. The estimation of the consequences of failure of dragline components is divided into two categories: loss of production (β) in terms of breakdown time of the system and its effect on the degraded performance (μ) due to occurrence of defect in the component of the system.

The average production losses due to failure of the capital-intensive dragline is categorised into five categories: negligible losses, minor losses, moderated losses, major losses, high losses in terms of breakdown time with the help of experts' opinion as shown in Table 2. In Table 2, τ is the average breakdown time of component per failure.

Table 2: Production loss of system in terms of average breakdown time loss

Criteria	Average breakdown time loss	Rank
Negligible losses	τ < 0.50 hours	1
Minor losses	0.50 < τ < 1.5 hours	2
Moderated losses	1.5 < τ < 5 hours	3
Major losses	5 < τ < 24 hours	4
High losses	τ > 24 hours	5

The occurrence of failure in the dragline system has degraded the performance. It is mostly due to occurrence of defect in the components of the dragline. The defect of the component of the system is categorised into five categories such as negligible defect, minor defect, major defect, critical defect and catastrophic defect, as presented in Table 3.

Table 3: Rank the performance of the system in terms of defect of the component

Criteria	Definition of criteria and its impact on dragline performance	Rank
Negligible defect	The system continues to work with negligible degraded performance.	1
Minor defect	The system is operable with reduced performance due to minor damage.	2
Major defect	The system is not operable but within the safety limit with major damage.	3
Critical defect	The system is inoperable and it can damage the particular component of the system.	4
Catastrophic defect	The system is inoperable with destructive damage of system without warning and safety.	5

Table 4: Evaluation of RPN of various components of the dragline

Subsystem	component	f	BT	Ʈ	α	β	μ	Φ	RPN
Bucket	Tooth point	25	31.25	1.25	5	2	2	1	20
	Socket	19	22.5	1.18	4	2	2	1	16
	Drag/hoist chain	21	29.75	1.42	5	2	2	1	20
	Drag/hoist chuckle	11	23	2.09	3	3	3	1	27
	Adopter	13	24	1.85	3	3	3	1	27
Rope	Hoist rope	2	13	6.5	1	4	3	1	12
	Drag rope	11	47.5	4.32	3	3	3	1	27
	Dump rope	17	26.5	1.56	4	3	3	1	36
	Intermittent rope	3	11.75	3.92	1	3	3	1	9
	Suspension rope	2	9	4.5	1	3	3	1	9
Main unit	MG set	6	64	10.67	2	4	4	2	64
	Hoist system	5	1468	293.6	2	5	4	2	80
	Drag system	16	2459	153.7	4	5	4	2	160
	Swing system	9	261	29	2	5	4	2	60
	Walking system	3	130	43.3	1	5	4	2	40
Structure	Boom	1	72.5	72.5	1	5	5	2	50
	Fairlead	1	56.5	56.5	1	5	5	2	50
Drive system	Generator drive	5	13	2.6	2	3	3	2	36
	Motor drive	6	19.5	3.25	2	3	3	2	36
	Exciter	3	5.75	1.92	1	3	3	2	18
	Auxiliary drive	7	17.5	2.5	2	3	3	2	36
	Controller	8	14	1.75	2	3	3	2	36
	PLC system	3	1.5	0.5	1	1	3	2	6
Lubrication system	Oil pump	2	48.5	24.25	1	5	4	1	20
	Pipe	1	39.5	39.5	1	5	4	1	20
	Oil filter	4	17	4.25	1	3	2	1	6
	Valve	1	3	3	1	3	2	1	6
Trailing cable	Sheath	1	3.5	3.5	1	3	2	1	6
	Metallic screen	1	12	12	1	4	2	1	8
	Insulation	1	11	11	1	4	2	1	8

4.3 Estimation of detectability of failure and its root cause

The detectability (Φ) of component failure can be defined in the term of identification of failure and its root cause so that maintenance action can be taken as soon as possible. The root cause of failures can be identified by various means such as operator ability, sensor, alarms, and by the maintenance crew to detect failure through naked eye or through observing vibration and unwanted sound during a scheduled inspection. When proven techniques are available to identify the failure and their root causes, they are ranked 1. Whenever proven technique is not available to identify the failure or its root cause and it is identified either through the sequence of the checklist provided by the manufacturer or identified through experts' opinion or through some rules (e.g., if-then rule) and they are ranked 2.

5. Results and discussions

The collected failure data of dragline is used to calculate the RPN using the rank of occurrence, losses, defect and detectability of the failure. The estimation of RPN for 30 components of the dragline is presented in Table 4. The RPN can vary between 1 and 250. The higher the RPN is, more critical will be the component of the dragline system.

The RPN of the dragline components can be a guiding tool to prioritise the maintenance planning. The lower RPN of the failed component, lesser in demand for preventive maintenance, and higher the RPN of the component, more focus can be put on the preventive maintenance. As calculated in Table 4, the prioritisation RPN of various components of dragline system is depicted in Fig.4.

Rather than the risk prioritisation of the individual components based on their RPN, it is also realised to group the components so that maintenance priorities of specific group of components can be understood and illustrated for better maintenance planning. Therefore, the critical failure components are categorised based on RPN into three groups: high-risk, medium-risk, and low risk components as presented in Table 5.

TABLE 5: CLASSIFICATION OF COMPONENTS BASED ON RPN TO PRIORITISE MAINTENANCE

Criteria	Linguistic Variable	Number of components	Dragline components	Maintenance rank
RPN≥80	High-risk component	2	Drag system and hoist system.	I
25≥RPN<80	Medium-risk component	14	MG set, swing system, boom, fairlead, walking system, dump rope, generator drive, motor drive, auxiliary drive, controller, drag/hoist chuckle, adopter, drag rope, and drag/hoist chain.	II
RPN<25	Low-risk component	14	Tooth point, oil pump, pipe, exciter, socket, hoist rope, intermittent rope, suspension rope, metallic screen, insulation, PLC system, oil filter, valve, and sheath.	III

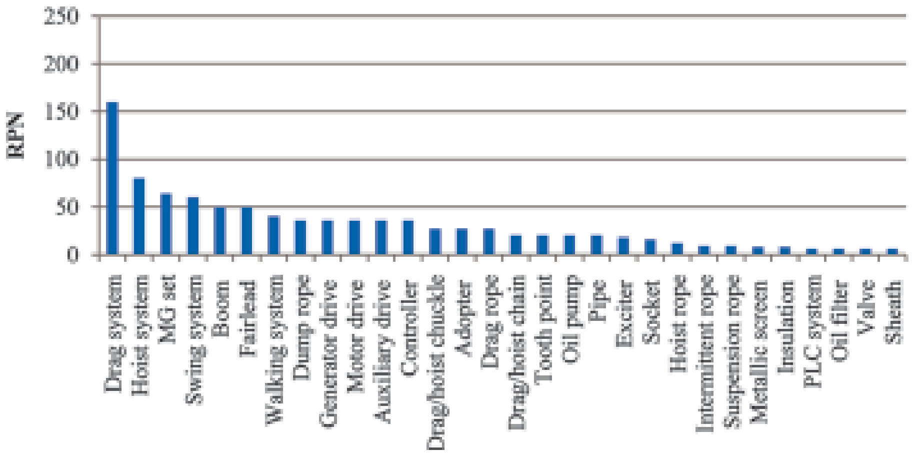

Fig.4 RPN of various component of dragline

The components belonging to the high-risk category (RPN≥80) needs more attention of the maintenance engineer and inspection interval of such components can be reduced to avoid unwanted failure of the dragline system. In this study, these dragline components are drag system and hoist system and they belong to the main subsystem of the dragline. The inspection interval (T) and inspection observation time (t) of various components of the dragline are fixed based on manufacturer recommended guidelines. Before optimising the inspection intervals and observation time of the components, it is assumed that the inspection activity is perfect so that it can catch any defect if it is available in the component requiring repair or replacement so that component becomes defect-free (Golbasi and Demirel, 2017; Golbasý and Demirel, 2017). Timely inspection of the component reduces the occurrence of failure in the component. To prevent the occurrence of failure in the high-risk components (referred for maintenance preference rank-I), it is needed to reducing the scheduled inspection interval from (T) to (T–ΔT) and more focus on preventive maintenance action to increase the predefined inspection time from (t) to (t +Δt) to avoid unwanted damages to the dragline.

For the medium-risk components of the dragline (25 ≤ RPN < 80), the scheduled inspection interval and predefined inspection time can remain unchanged. For low risk components (RPN < 25), referred for maintenance preference rank-III, the scheduled inspection interval (T) of components should be increased to (T+ΔT) and the predefined inspection time can be decreased from (t) to (t – Δt) to avoid unnecessary inspection of dragline system.

Future study is to optimise the inspection time interval (ΔT) and inspection time (Δt) including the parameters such as cost of inspection, profit per unit time, output loss due to inspection, resources availability, inspection method, and remaining useful life of the component to find scheduled date and time for inspection of various components of the dragline.

6. Summary

The occurrence of failure due to improper maintenance activities leads to downtime losses, and it reduces the availability, reliability and productivity of the system. In this paper, thirty critical components of the dragline are identified using FMECA. The estimation of RPN using occurrence, production losses, degradation in performance of the component, and detectability of failure helped to qualitatively assign a risk score to the critical component of the dragline. The RPN is used to classify the critical component into three groups to optimise the preventive maintenance schedule of dragline to reduce the failure of the dragline. The methodology is equally applicable for risk assessment of sophisticated and capital-intensive HEMMs deployed in the construction industry, mining industry and agriculture industry for achieving timely maintenance strategy.

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