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Managing the Integrity of Mine Cage Conveyance using Fault Tree Analysis

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***Abstract*— The mine cage conveyance is a critical piece of equipment in an underground mine as they are considered as the lifeline for transporting miners and equipment to an underground mine.**

Considering the criticality of the mine cage conveyance, managing its integrity for the safe operation has become a priority as failures resulting from their operation can become catastrophic.

This study shows how fault tree analysis can be used to analyze failures associated with the mine cage conveyance while showing the various branches of events that can lead to such failures and their order of criticality for the various associated components.

Keywords*— *CMMS; FTA; TTF; TTR; MTTR; MTBF; Cage; Mining; Reliability; Conveyance; FTA; Criticality.

I. INTRODUCTION

In the world, the mining industry has become an integral part of the economic development in several countries, as the need for minerals (e.g., Nickel, Copper) has increased due to their wide range of applications, especially in the production of alloys. However, like every other industry in the world, the mining industry is prone to accidents and fatalities as reported statistically by the International Labor Office, over a hundred and twenty million occupational-related accidents occur annually across various industries in the world, while the mining industry records a substantial proportion of these fatal accidents. [1].

Mining as an occupation has been considered as one of the world's most dangerous professions as shown by the mine safety and health administration [2]. This was further confirmed with a fatality information survey conducted in the United State, between 1980 to 1995 on occupational injury rates, which showed that the mining industry had the highest injury rate [3].

Failures resulting from unexpected equipment and asset breakdown have caused great injuries and fatalities to personnel while leaving the organization with a huge financial loss. Therefore, the safety of the mines does not exclusively rely on their design and operations, but essentially on the effectiveness of the maintenance strategies employed to enhance consistent and reliable day-to-day operations.

The purpose of this study will focus on managing the integrity of the mine cage conveyances as a piece of critical equipment with emphasis on reviewing the associated failure modes and determining the reliability of the mine cage using the Fault Tree Analysis.

II. THE MINE CAGE CONVEYANCE

The mine cage conveyance, which is said to be the lifeline for miners, has become an essential part of an underground mining operation, as they are considered the safest and most reliable means of transporting miners, equipment, and necessary materials to and fro the ore body. However, these conveyances are prone to failures, which can result in critical incidents, such as the 1973 conveyance disaster, which took place at the Markham Colliery in Derbyshire, UK, where an overwound conveyance fell to pit bottom resulting in the death of seventeen people [4].

The choice of transportation significantly contributes to the rate of profitability and production to the organization, as it could improve production while adversely reducing the effect of costs.

Various factors determine which mode of transportation should be considered, such as the depth and life span of the mine, its operational cost, and the projected production rate [5].

For mines whose depth is not so deep, they can conveniently transport miners and equipment to and fro underground, with the aid of a haulage truck via the ramp. However, in Canada, the mine cage is the common and safest means of transporting personnel and equipment as its mines have a depth greater than 4000 meters.

III. CAUSES OF MINE CAGE CONVEYANCES FAILURES

Some of the major causes of mine cage conveyance failures include failure of the safety catches, popularly known as safety dogs, failure in the hoist rope attachment, the braking system of the cage conveyances, and structural failure due to wear and tear from the environment.

Like in Canada, and other parts of the world, most mine shafts are designed with a wooden guide and the cages are furnished with safety catches. These safety catches should serve as redundancies to the hoist rope and are meant to be activated at the failure of the hoist rope or when it has lost the required tension needed between the rope and the attachment. [5].

Additionally, the tensioned hoist rope helps to prevent the teeth of the safety catches from the shaft guides, and as soon as the tension in the hoist rope is lost, the safety catches are activated in the guides with the aid of spring and not considering at what speed it was traveling the cage comes to a halt [5].

Most hoisting systems like the cage conveyance are constantly used at a high speed while traveling underground, it usually runs at about 600 feet per minute [13].

Furthermore, failure resulting from the cage conveyances could be fatal and result in a potential loss just as it was recorded in February 1945 at the paymaster mine, Ontario, Canada, when the hoist rope broke, and the safety catches (safety dogs) could not avert the cage from falling which sadly resulted in the death of sixteen miners [6].

Fault Tree Analysis

This study will be looking at the root causes of cage conveyance failures and ways to mitigate them using Fault Tree Analysis.

Fault Tree Analysis is one of many analytical techniques that can vigorously establish the cause and consequences of system failures. FTA is considered a detailed deductive analysis that requires specific information about undesirable events [10].

The complexity of many systems makes it difficult to carry out an effective analysis when failure has occurred, this created a gap in determining the root cause of failures and preventing such reoccurrence in the future. However, fault tree analysis has considered this gap by ensuring that all critical component of a system is identified and controlled.

A top event that is depicted with a rectangular box usually indicates the start of the fault tree analysis, this is closely followed by other interrelated gates and events which branch off the tree based on rational connection with the top event [12]. The fault tree analysis uses different symbols which give different meanings, and a brief explanation will be provided below.

The basic events which are represented with a circle indicate that there is no further development, while the diamond shape represents undeveloped events, and it shows that there is no availability of data.

A transfer is done in fault tree analysis with the symbol of the triangle which indicates development at other trees [7].

The "AND" gate indicates that the output events occur when both input events occur. This further shows the connection of the groups comprising of all the input events to the specific gate. While the output from the "OR" gate occurs when one of the input events occurs. This defines the combination of the groups comprising of all the input events to the specific gate [7].

Some commonly used symbols and what they represent in fault tree analysis are depicted in Table 1.

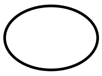
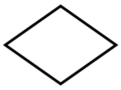
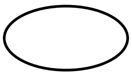
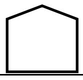
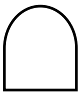
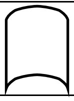
S/N	*Symbol*	*Description*
1		Primary or basic failure event. It is a random event, and enough data is available
2		State of system, subsystem, or component event
3		Secondary failure or underdeveloped event can be explored further
4		Conditional event and is associated with the occurrence of some other event
5		House event representing either occurrence or non-occurrence of an event
6		The output occurs when all the input events occur
7		The output event occurs when at least one of the input events occur

Table 1 Fault tree symbols [12]

Fault Tree Analysis Flow

In developing a typical fault tree process, six basic steps are used as shown in Fig. 1 below.

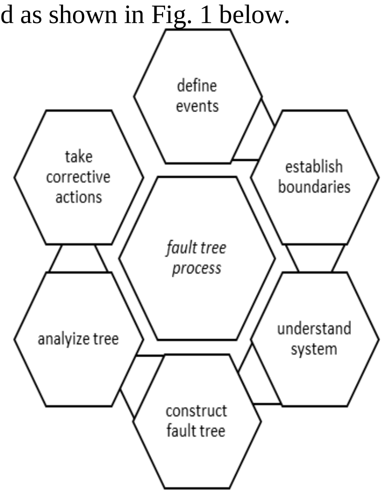


Fig. 1 fault tree analysis process [8]

Logic gate possibility of occurrence

To evaluate the possibility of a top event occurring, it is pertinent to evaluate the possibility of output fault events of the logic gates occurring. Hence "AND" and "OR" gates possibility of occurrence can be deduced with the equation shown below [9]

- ***For AND gate***

$$P(X_a) = \prod_{j=1}^{m} P(X_j) \qquad (1)$$

Therefore P(Xa) = possibility of occurrence of AND gate's output fault event Xa.

- ***For OR gate***

$$P(X_O) = \prod^{m} P(X_j) \qquad (2)$$

$j=1$

Therefore, m represents the number of input fault events, while the possibility of occurrence of OR gate's output fault event Xo. P(Xj) represents the possibility of occurrence of inputs fault event Xj, for j =1,2,3 ......m.

Note: The logic symbol used can be depicted in Fig. 3 below.

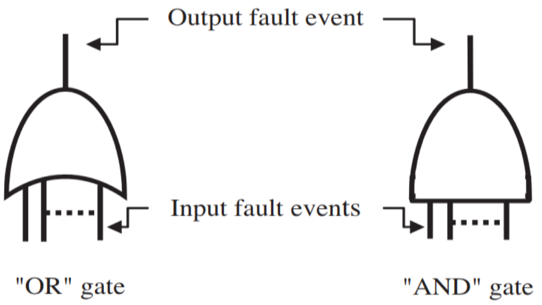


Fig. 2 fault tree analysis logic symbol used [7]

Associated Failure Modes of Mine Cage Conveyance

Mine cage conveyance maintenance approach and reliability in service is key to the safe operation of the mines, however, despite putting measures in place to prevent failures of the mine cage conveyances, some failures are inevitable which means some components within the system will fail during the life span of the overall system.

Some of the recorded failures are due to the normal wear and tear experienced from daily operation, to this end it becomes imperative for maintenance personnel to address critical system/component failure that can affect the entire system.

Table 2 shows some of the components of the mine cage and associated failure modes

Mine Cage Conveyance – Subsystem and Failure Modes	
Subsystem/Component	***Failure Mode***
The Breaking System	Failure due to caliper wear Break disc misalignment
The Shaft Guides	Guide's misalignment, loosed guides, bolts, and bracket. The defect on timber and corrosion
Safety Catches	Corrosion clogged and spring failure
Hoist Rope	Failure due to corrosion, wear, and tear. Failure of the attachment
Structure	Concrete deterioration and failure of concrete lining due to wear

Table 2 Mine Cage Failure Modes

Case Study

The purpose of this case study is to determine the probability of failure occurrence in an underground mine cage conveyance located in Ontario, Canada with the aid of a Fault Tree Analysis to trace all branches of event that contribute to the failure of the top gate, in other words.

Failure Data Collected

The data required for this case study were obtained from the computerized maintenance management system (CMMS) which includes daily reports and work orders raised within 24 months showing the meantime to repair (MTTR) for various failed components.

Subsequently, a review of the data collected was done which facilitated the calculation for the probability of failure occurrence for each system and sub-systems using the Isograph reliability workbench.

Table 3 shows the data obtained within the period under review

Associated Failure	***MTTR***	***Failure Rate***	***MTTF***
Conveyance wheels	3	0.000694444	1437
Shaft guides	10	0.000952381	1040
Cement side	4	0.000641026	1556
Door latches	5	0.001262626	787
Shaft Door Hinge	2	0.002314815	430
Ground Conditions	8	0.00154321	640
Divider Beam	2	0.000925926	1078
Wire mesh brattice	8	0.001302083	760
Cage guide	6	0.000925926	1074
Brattice beam	7	0.000641026	1553
Conveyance hi water probe	3	0.001602564	621
Coupling	3	0.001893939	525
Sheave	8	0.001157407	856
Cage Access Door	8	0.001488095	664
Cage alignment	4	0.001436782	692
safety catches	5	0.000520833	1915
Hoist rope	2	0.002083333	478
Wheels – Rubber damaged	4	0.001190476	836
Brakes	2	0.002777778	358

Table 3 Data Obtained from CMMS

The mine cage conveyance is divided into various subsystems showing the combination of component faults that could result in cascading failures, leading to an overall system failure as shown in Fig. 3.

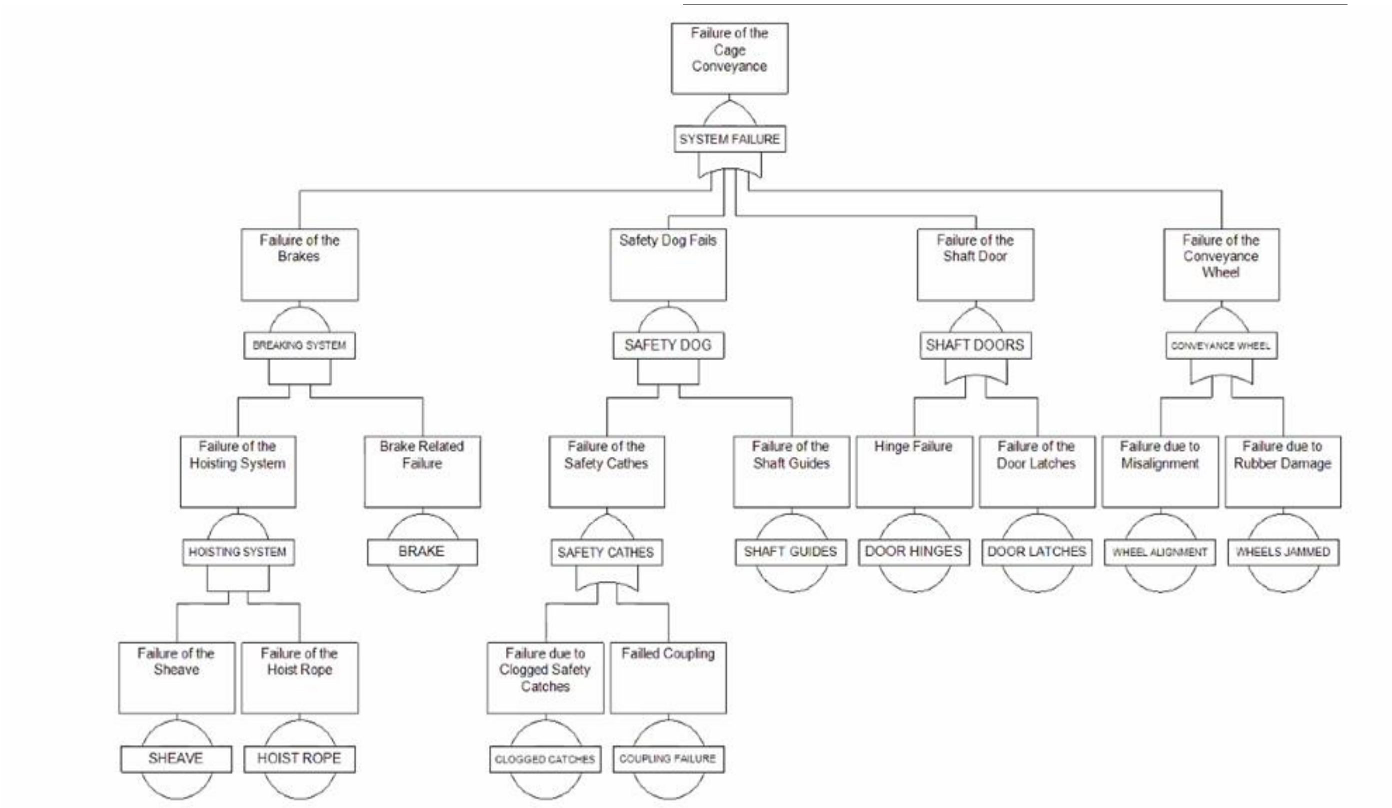


Fig. 3 fault tree analysis

Result Outcome

The result summary from the Isograph workbench represented in table 4 below shows the various failure matrices and their respective calculated values. The mine cage conveyance will reach unavailability of 0.56% with a conditional failure rate of 0.007, which signifies the failure rate per unit time that a failure will arise in the mine cage conveyance system or one of its associated components.

Some significant failure prediction values also calculated are, the frequency of failure, unreliability, and risk reduction factor, which not only aids the decision of maintenance engineers when scheduling maintenance task frequency but also helps in risk modeling and safety optimization.

Gate ID	*Description*	*Parameter*	*Point Value*
System Failure	Failure of Cage Conveyance	Unavailability	0.005663
		Frequency	0.006975
		CFI	0.007015
		Number of Expected Failures	0.006975
		Unreliability	0.006991
		Total Down Time	0.005663
		Mean Unavailability	0.005663
		Risk Reduction Factor	176.6
		Q/T	0.005663
		Used Method	Cross Product

Furthermore, the result showed components with high level of criticality that plays a major role in the safe operation of the mine conveyance with their order of criticality as shown in the figure below.

Table 5 also shows the cut set representation of individual components that should be prioritized when carrying out planned maintenance, due to their high probability of failure and low availability.

Gate ID	*Description*	*Q = Availability*	*Minimal Cut Set*
System Failure	Failure of Cage Conveyance	3.963E-09	Breaking System
		1.795E-06	Safety Dog
		0.004019	Shaft Door
		0.001649	Conveyance Wheel

Table 5 level of component criticality

While developing maintenance plans and strategies, the focus should be deplored in these areas of high criticality to mitigate against such failures as shown in table 5 above.

Conclusion

This study has further reinforced the importance of the mine cage conveyance in an underground mine operation.

Failures associated with one or more components as shown in the logic tree above can compromise the effectiveness of the mine cage conveyance as a system as such, efforts must be placed on managing the critical components identified in this study with a great focus geared towards reviewing the existing maintenance plans and developing more robust strategies (preventive and predictive approach) to avert such unwanted failures to the system.

Conclusively, effective maintenance improvement methodologies such as Six Sigma and Reliability Centered Maintenance which utilizes fault tree analysis as one of the tools will be beneficial to the organization as it will boost profits, reduce the cost of repairs and emergency work breakdown notification and improve the safe operation of the mine.

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